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Operating Policy Adaptations For A Reservoir System

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TECHNICAL REPORT 79

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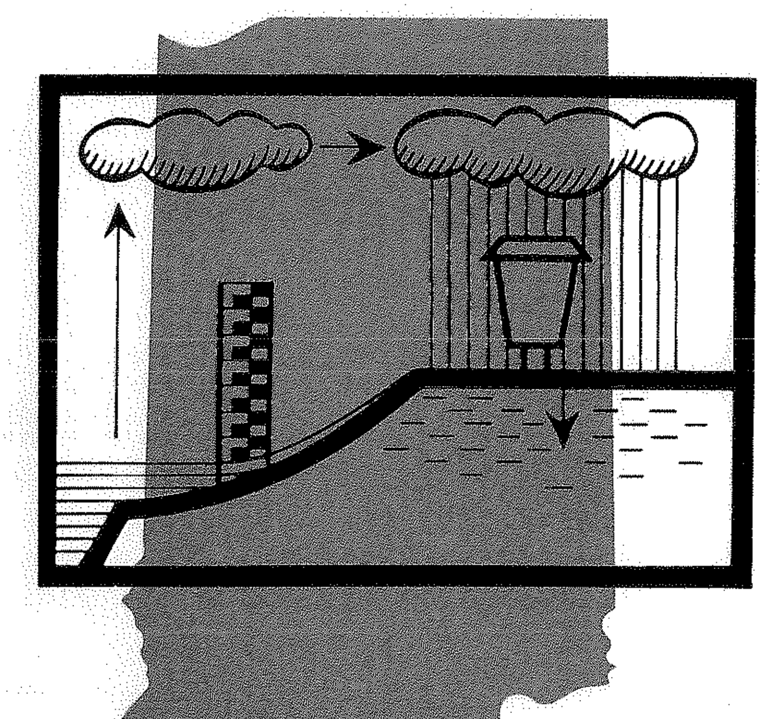

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PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
WEST LAFAYETTE, INDIANA

Water Resources Research Center
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OPERATING POLICY ADAPTATIONS FOR A RESERVOIR SYSTEM

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OPERATING POLICY ADAPTATIONS FOR RESERVOIR SYSTEM

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TERMINAL REPORT OWRT - 14-31-0001-9083
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PREFACE AND ACKNOWLEDGEMENT

The origins of the study reported herein date back to river basin simulation projects sponsored by OWRR via the Purdue Water Resources Research Center. That earlier research involved building a computer simulation model for the 8000 mi^2 Upper Wabash River and Reservoir System. A recognized incompleteness of the effort was the attempt to incorporate the Corps of Engineers stated regulation plans into the simulation model. In fact, two reservoir balancing rules were used which, as such, were not part of the official regulation rules.

Accordingly an OWRT-supported research was initiated to study the regulation rules or "operating policies" for one or more existing reservoir systems. The study would concentrate on comparing the stated operating policy with what had actually happened, again using a simulation model approach.

Particular attention would be given to changes or "adaptations" in operating rules. An attempt would be made to relate the adaptations to their origins (e.g. interest groups, physical factors, progress in data handling and systems analysis, etc.) and to their associated objectives (e.g.: economic efficiency, environmental quality, recreation, etc.).

The results of the first phase of this study which was limited to the 8000 mi^2 Green River Basin in Kentucky, are reported herein and in a companion report (PWRRC #80) which amplifies certain aspects in more detail.

A daily simulation study for the regulation of a system of four major surface reservoirs is a fair-sized undertaking that could be finished only partially. Even that could not have been accomplished had it not been for the willing cooperation of the COE Louisville District Office Staff, of its Engineering Division, Bill Leegan, Chief; its Hydraulics Branch, N.M. Whittle, Head; and, in particular, the staff members of the Reservoir Regulation Section, Bob Biel, Head, and Messrs. J. Jarboe, R. Lehman, G. Presley, and P. Roberson, staff members.

Considerable help and support was received also from the COE Cincinnati Division Office, particularly from G. T. Mitchell, Head Hydrology Branch, and its Reservoir Control Center Staff, especially Messrs. Dave Halsey and Ronald Yates. Mr. Carl Flener who headed the Louisville Reservoir Regulation Section during much of the period analyzed herein, also provided valuable assistance.

Major contributions to the project were made by Mr. W. C. Boswell, now at the COE Nashville District Office and by Dr. Y. S. Lin, now at Stone and Webster, Boston, Mass. Mr. Boswell was involved, while at Purdue University, in the initial attempts to cast the reservoir regulation guides into a simulation model form, called "operating policy algorithm." Dr. Lin improved the model considerably and was involved in the enormous data collection and handling task. Support for the latter in the form of a flexible Data Base and associated routines was provided by T. Sullivan. The reservoir inflow model construction was performed under supervision of Drs. Tao and Rao. During part of the period the project was supervised by Dr. J. W. Delleur of Purdue University's School of Civil Engineering. Administrative support was provided throughout the period of project inception through the completion of the current phase by Dr. D. Wiersma, Director Purdue Water Resources Research Center.

Last but not least the authors would like to acknowledge Sherry Miller for her expert typing of draft and figures.

ABSTRACT

Daily reservoir regulation records in the form of historical daily releases, Q_{ht}[cfs], were constructed for the four Corps of Engineers reservoirs in the Green River Basin, KY. The Q_{ht} time series were constructed from the daily Dam Tender Reports for the Barren, Green, Nolin, and Rough River Reservoirs, KY.

The Q_{ht}-values were compared on a day-by-day basis with the release decisions, Q_t, yielded by an operating policy algorithm based on the official Reservoir Regulation Schedules. These schedules are merely guides and will, in practice, be supplemented by various rules and practices. An attempt was made to capture these practices in an operating policy algorithm. The building of the models to obtain Q_{ht}, Q_t, and the various exogeneous data series needed by the operating policy algorithm, constitutes the major aspect of the work reported herein.

An initial analysis of the results, mainly in the form of daily flow deviation series, Q_{ht}-Q_t, for up to eight years and four reservoirs has provided considerable insight into the many practical constraints associated with the operation of an actual reservoir system. This is of value to researchers in reservoir systems analysis. Further analysis involving interviews with COE staff are needed to exploit all the computed data series. Initial analysis points to possible improvements in computer assisted operations of reservoir systems.

OPERATING POLICY ADAPTATIONS FOR THE GREEN RIVER BASIN RESERVOIR SYSTEM

I. PROBLEM STATEMENT AND OBJECTIVES

In 1969 a seminar was sponsored by the Corps of Engineers' Hydrologic Engineering Center. The meeting, intended for Corps of Engineers staff, dealt with problems and techniques of reservoir systems analysis. The seminar objectives were to:

(a) exchange field level operation concepts;

(b) identify specific reservoir design and operations problems;

(c) expose those present to potential problem solutions involving the use of operations research techniques;

(d) promote use of systems analysis techniques at the District Office level.

The resulting seminar proceedings[1)] are to date still the best available source of information and practical opinions on the day-to-day operation of actual reservoir systems.

In his incisive summary and conclusions at the close of the seminar Leo R. Beard, then HEC's Director, listed problems and needs that had been aired. He confined himself to problems and needs that at least involved COE staff active in engineering design, operations, research, and the management thereof. An interpretive abstract of that list is as follows:

1. ADMINISTRATIVE PROBLEMS

(a) Reluctance in offices to fully document problems, presumably for fear of criticism. As a result too little was done agency-wide to avoid them.

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1) ———————— : *"Reservoir Systems Analysis", Proceedings HEC Seminar, Corps of Engineers, Davies, California (1969)*

(b) Frequent need to plan a component (e.g. a reservoir) in such a hurry (politics of authorization) that its role as a systems component (incl. the constraints it imposes on existing components) is not being looked at.

2. *PERSONNEL PROBLEMS*

(c) Inclination to use familiar and self-made tools rather than adapting one produced by others. In regard to methods involving computer programs this tendency is too easily defended because of frequent inadequacies in documentation.

(d) Seat-of-the-pants operation of reservoir systems can persist where that responsibility is entrusted to one individual and where (often as a result) it is not explicit and open to study (as would be possible by the use of well-documented and widely reported computer algorithms that would be familiar to more regulation staff).

(e) Conversely, builders of simulation algorithms often do not recognize the complexity of someone else's problem and promote inapplicable programs.

3. *ENGINEERING PROBLEMS*

(f) The lack of systems design in building a reservoir system. It more or less grows in time; new additions impose often unintended constraints on what exists. The whole was experienced as being extremely "complex" and very difficult to regulate.

(g) The problem of complexity was compounded by recent increases in the number of project purposes (reflecting added objectives) and their being season-dependent.

(h) The high degree of fidelity required of models. Only more study and simulation models held out hope.

(i) HEC simulation models appear to promise a capability to cope with increasing complexity. Even then problems remain, namely the voluminous output of simulation, the difficulty of how to define differences between different outputs, and how to make operating policy changes to obtain desired differences.

(j) The need to use several simulation models to study different aspects of a single study. The problem is that this is costly. Yet a very flexible computer program can also be expensive and can be difficult to use.

(k) Operations research methods still had not proven their value, except insofar as they encourage future development of the techniques.

4. SUMMARY OF NEEDS

(l) A practical handle on the multi-objective problem and the formulation of a relevant objective function useful in reservoir operation.

(m) A need to pre-program decisions that are now largely subjective in actual operation.

(n) Methods to actually optimize the design or the operation of a reservoir system given its overall objective(s).

(o) A need to further develop and use stochastic process analysis results and then to assess their utility.

(p) A need for a much broader treatment of the reservoir operation problem. Contingency operations, water quality programming, much better field data are essential.

(q) A need for good communication between agency engineers and the academic community. Therefore there is a need for agency engineers to better communicate problems to academic researchers and a need for academicians to better describe the reasons for "advanced techniques" as well as to cooperate in adapting them to practical use.

5. CURRENT STUDY AND ITS OBJECTIVES

As of 1976 the above tabulation still appears up-to-date. The study reported herein is held to represent a small contribution to meeting some of the problems and needs listed by Beard (1969). Thus, by way of introducing the study, an attempt will be made to relate facets of all those problems and needs to aspects of this study. The result of this search for relations is shown in Table I - 1.

LISTED PROBLEM OR NEED	SELECTED FACET	RELATED ASPECT OF CURRENT STUDY	REFERRED TO IN SECTION[1)]
A	B	C	D
1-a	full use of available reservoir regulation data	1. utilization of dam tender reports	III-3,VI-5 II-5
1-b 3-f	fitting of new reservoir into a system	2. systems aspect of current operating policies	IV-2,V-1 VIII-3
2-c, d	little use of generalized (e.g. HEC) algorithms in reservoir systems	2. efforts to analyze the problems of translating regulation procedures into algorithmic form	V-1,2,3 VI-1-8
2-e	systems analysis models that do not adequately reflect practical constraints and influences	4. efforts to interact with reservoir regulation staff about a specific system	III-1,2 VI-5,6 VIII-1,2
3-g	difficulty to handle multi-objectives; growing complexity due to addition of objectives	5. ex post evaluation of adaptation of new stated regulation policy to new objectives	II-1,3 VI-3,4 VII-1-6
3-h	the high degree of fidelity needed in simulation models	6. the marginal value of increasing accuracy and of additional data	VI-5,6 V-6
3-i	volume of simulation model output, its evaluation for incremental changes	7. the role of graphic output and its use	IV-2 VI-1,5
3-j	generalized versus very specific, local models	8. study of specific system, namely reservoir regulation for Green River Basin, Kent.	III-3 II-1
3-k	no use of operations research methods	9. applicability of O.R. methods in daily regulation	II-1,2
4-l	problem of handling and weighting multiple objectives	10. can weighting of objectives be inferred from historic operation records	VII-6, VIII-2
4-m	need to pre-program now subjective regulation	11. use of models with forecasting and optimization	III-5,V-4 VI-2 V-6 VI-3

A	B	C	D
4-n	optimization	12. optimization	V-4,VIII-3
4-o	generated data series	13. generated data series	III-5,VI-2 V-2
4-p	adoption of broader view	14. planning and design implication inferred from historical regulation records	VII-6 VIII-1
4-q	communications between COE and academia	15. interviews and discussions between agency and university staff	III-1,2 VI-5,6 VIII-1,2

TABLE I - 1 - CORRELATION OF SELECTED FACETS OF PROBLEMS AND NEEDS (ACCORDING TO BEARD IN 1969) TO ASPECTS OF THE CURRENTLY REPORTED STUDY

[1] Column D entries in cursive refer to PWRRC Report #79 sections; the entries in Gothic script refer to PWRRC Report #80.

The original research project objective was to study the adaptations made (in the course of time) in the operating policies of specific large reservoirs or reservoir systems. The selected reservoirs would be those belonging to the Wabash Basin, Ind., and the Green River Basin, KY.

The research on adaptations in reservoir operating policies attempted to identify the origins of the adaptations (interest groups, technical factors, systems analysis, etc.) and to identify the associated general objectives (e.g. economic efficiency, environmental quality, recreation, etc.).

The problem of actually finding and characterizing operating policy adaptation turned out to consume most of the available resources. Consequently, the original intent to study reservoir systems in Indiana, Kentucky and Tennessee, had to be limited to the study of a four-reservoir system in Kentucky. Thus, broad, sweeping conclusions based on adequate statistics have not been reached. Instead, much detail and related questions have been considered.

A somewhat reoriented, but possibly more profitable and practically relevant piece of research was accomplished as may be inferred from Table I - 1. The Table I - 1 shows how various aspects of the completed research relate to many facets of field level problems.

The conclusions that were reached are based only partially on the computer aided analysis. For another part visits with agency personnel provided valuable insights. It will therefore be helpful to relate more fully how the study was conducted and what were its underlying theses or points of departure.

II. POINTS OF DEPARTURE AND PROJECT OBJECTIVES

1. *ORIGINS OF STUDY*

The present study originated from earlier simulation model research for the reservoir system that was planned for the Upper Wabash River basin in Indiana.[1] The initial intent of that study was to adapt systems analysis tools of the operations research type to the planning analysis accomplished up to that time (1968). The position was taken that tools such as mathematical programming could be significant only in one of two cases: (a) during the very beginning of planning and in defining very large reservoir systems (so-called "screening"), or (b) as a small part in a considerably larger simulation model. Since the Upper Wabash reservoir system had been designed, only item (b) remained. As a consequence work was done on a simulation model for the Upper Wabash and its up to five reservoirs (3 built, 2 in contention and presently in the process of being de-authorized).

During the Upper Wabash study two things were accomplished. First, a certain amount of understanding was built between state and federal agency staff members. Secondly, a fair sized reservoir-river simulation model was built. Its key element was the simulation of the Corps of Engineers operating policy. Interesting results on reservoir-river systems control were obtained. Systems balancing policies were shown to be more "control effective" than the stated reservoir regulation schedules.

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[1] *"Simulation Model for the Upper Wabash Surface Water System," G. H. Toebes and T. P. Chang, Purdue Water Resource Research Center Report No. 27, (July 1972).*
"Operating Policies for the Upper Wabash Surface Water System," T. P. Chang and G. H. Toebes, Purdue Water Resource Research Center Report No. 31, (Dec. 1972).
"Initial Results from the Upper Wabash Simulation Model," T. P. Chang and G. H. Toebes, Purdue Water Resource Research Center Report No. 33, (March 1973).

Parallel efforts to use explicit optimization (LP, DDDP) merely led to academic results. The associated operating policies were incapable of reflecting real-life conditions. It was concluded that the utility of OR derived methodology in the daily operation of existing systems would likely be confined to sub-routines. Systems operators might use such sub-routines to refine regulation under critical circumstances where stochastic forecasts led to problems of choice of considerable dimension.

Unfortunately, no developmental work in that direction existed; by and large researchers seemed oblivious of the many details that govern the day-to-day operation of existing reservoir systems. Except for the HEC Seminar Report (see Chapter 1) no coherent literature on the subject could be found (in 1972).

2. *POINTS OF DEPARTURE*

Thus the following theses or points of departure (largely based on the Upper Wabash systems study) were adopted for the current study on regulating practices for existing reservoir systems:

(a) actual benefits result from real systems via real operating policies;

(b) increasing actual benefits from existing systems results from incremental improvements in existing operating policies;

(c) existing operating policies can be improved by increased use of simulation programs that:
   (i) are specifically tailored for the system at hand;
   (ii) posses great fidelity;
   (iii) can draw upon stochastic optimization sub-routines to refine the solution of delineated problems of choice;

(d) the developmental work to utilize mathematical programming techniques can only commence when existing operating practices and associated constraints are well understood and properly documented;

(e) a study involving such documentation and analysis of existing operating practices can not be undertaken without cooperation from the responsible operating agency.

3. PROJECT OBJECTIVES

These conclusions led to a principal objective of the study reported herein, namely a post-audit study of reservoir regulation and their stated operating policies for one or more existing systems.

The data generated by such a study, if sufficiently extensive, would permit the isolation of operating policy adaptations made in the course of time. In view of the then (1968-72) current question how responsive operations were or could be to changes in social objectives (e.g. recreation, environmental quality), the ultimate objective selected for the study reported herein was the identification of the origin[1)] and effects[2)] of operating policy adaptations.

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1) *Post-construction experience; expansion of system; demands by interest groups - agricultural, power industry, water supply, recreation, flood-plain users; river convoyance decrease due to changes in hydrologic regime; institutional policy changes - new standards, modified multi-objectives, impact statement; analysis studies - systems simulation, systems optimization)*

2) *national economic efficiency, environmental quality, regional and local social well-being effects)*

III. CONDUCT OF PROJECT

As stated, cooperation from the operating agencies was essential. In addition it was expected that such cooperation was needed across hierarchical divisions within an agency. Therefore, the work was initially approached somewhat different from the usual "desk-type" study. A brief account of its conduct is as follows.

1. *PREPARATORY CONTACTS*

The initial problem was to obtain documentation of historic operations for existing reservoir systems. Changes in operating policy as well as field level detail were desired. In view of earlier contacts, Corps of Engineers staff was contacted first. It was learned that proposals for operating policy changes are initiated at the COE District Office level. Approval is requested, via a Division Office, from the Office of the Chief of Engineers. Correspondence supporting the proposed change is filed by COE Division and data, together with all other correspondence. Collating material of interest, if done for many reservoir systems, would have to be done in Washington. Furthermore, support from the Chief of Engineers Office for requests at the Division or District levels, was thought to be essential. Similar procedures were assumed to exist at TVA.

Thus the following trips were made:

(1) Visit with the Deputy Chief of Engineers, General Rollins, Chairman of the Board of Rivers and Harbors, Washington D.C. A letter was obtained from General Rollins that requested the cooperation of Division and District Offices in the Adaptation of Operating Policy study.

(2) Visit with selected staff members of the COE Institute of Water Resources Research, Alexandria, VA. Discussion with the superior of Captain Locurcio (see below).

(3) Visit to COE's Ohio River Division Office, Cincinnati, OH. Discussion with staff of the Reservoir Control Center Staff; cooperation was promised.

(4) Visit to COE's Louisville District Office, Louisville, KY. Discussion with the District Engineer (Colonel Fiala) and with staff of the Reservoir Regulation Section. Operating data for Mansfield Reservoir, Indiana, were promised.

(5) Visit with Reed Elliot, Director Division of Water Control Planning, Tennessee Valley Authority, Knoxville, TN and with key staff members of that Division who were involved in coordinating operations with COE's Louisville District and Ohio Division Offices during periods of severe flooding (COE assumes operating responsibility of some TVA storages during such periods).

2. *PERSONNEL SELECTION*

Anticipating work that involved a search of correspondence and report files kept in Board of Rivers and Harbor Offices, Washing D.C., a certain Captain R. Locurcio was attracted as project staff. It was arranged that Captain R. Locurcio, having completed all course work would do a Purdue thesis in absentia. He became assigned to the COE Institute for Water Resources Research in the section to which the Purdue group had explained the Adaptation Project. What seemed an unusually fortunate circumstance turned into time loss when Captain Locurcio's leave was abridged, full time work was assigned within the IWRR, and thesis work precluded.

The first project conclusion was thus obvious: institutional boundaries and objectives can impede water agency-academic staff cooperation in research. This further posed the question what to do about the frequent complaints about university water resource research studies that were impracticably academic and lacking in real world data.[1] Was the current study which took the need to bridge the use-research gap as a point of departure, a feasible, legitimate, or desirable exercise?

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[1] *Gilbert White on page 14 of "Strategies for American Water Management," Univ. of Michigan Press (1969), formulated this as follows: "The shelves are bursting with ..... normative studies of optimal solutions. A few inches will suffice to record what is known, in fact, to have happened,".*

3. RESERVOIR SELECTION AND OPERATING DATA ACQUISITION

During a day-long conference (August 9, 1973) at the COE Louisville District Office it was decided to select the Mansfield Reservoir in Indiana for a detailed study of a historic operating policy. Various data retrieval efforts proved to be time consuming. The last records that completed the daily information data pertaining to the Mansfield reservoir were received half a year later (February 4, 1974). In addition, about 80% of the records for Mansfield Reservoir were in graphical form. Originally plotted on red graph paper the Xerox copies received rendered,part of the graphs illegible. All conceivable ways were considered to fill in and to automatically digitize the information; no practical method was found. As a consequence copies were needed from hand-written daily dam tender reports kept at a central storage facility in Kansas City.

In addition to dam tender report data, a number of stream flow records were needed at locations as far downstream as the Ohio River. The flow rates at those so-called control stations were part of Mansfield Reservoir regulation guidelines. All in all it turned out that:

(a) available USGS records were incomplete;

(b) one of the stations (Little Raccoon Creek) had been discontinued (1970);

(c) dam tender reports were not uniformly formatted and doubts arose as to their interpretation;

(d) an outflow constraint had developed at Mansfield that masked other operations adaptations.

Finally, preliminary study of the Mansfield records with available records of flow in the Upper Wabash suggested that the coupling between the Mansfield Reservoir operation and that of the three Upper Wabash reservoirs (Huntington, Salamonie, and Mississenewa) was weak. Thus it was decided:

(a) to use the Mansfield information for the initial attempt to cast the operating policy into algorithmic form,

(b) to obtain dam tender reports for reservoirs more representative of a system, namely the four reservoirs of the Green River Basin (or GRB, for short) in Kentucky (see Figure III-1). Digitizing the dam tender reports for the GRB reservoirs proved to be laborious (see the companion report PWRRC Report #80).

It was surmised that:

(a) one factor that impeded the development and application of realistic systems analysis procedures is the problem of digitizing historical operations data;

(b) probably under pressure from tasks at hand, design and operations branches could give little priority to an analysis of all historical records for studies of the "planning type";

(c) on the other hand, planning branches found the scope of their work becoming so catholic that a study of historic operations data could not be budgeted.

4. *OTHER DATA NEEDS*

In addition to voluminous dam tender report information, about 10 years of over 20 historical stream flow and precipitation data series were needed for locations in and around the Green River Basin. Also pan evaporation data were required to construct reservoir inflow models. All this made design of a suitable Data Base structure necessary. The Data Base required, in turn, appropriate access and modification routines. Details are given in the companion report PWRRC Report #80.

5. *RESERVOIR INFLOW FORECASTING MODELS*

It is possible to use the dam tender report data to generate estimated reservoir inflow time series. These time series can then be correlated with precipitation records obtained in and around the contributing watershed to yield a reservoir inflow forecasting model. Having this model one can use it, together with the precipitation data for a given reservoir controlled watershed, to approximate the reservoir inflow forecasts which, as was concluded during a later stage of the project, played a definite role in the historical reservoir operating decisions.

For Rough River Reservoir such an inflow model was constructed. It is a stochastic model that involves the contributing "watershed storage" as a key variable. Similar models for the other three reservoirs could not be completed within the available time. Deterministic inflow series deduced from dam tender data have been used in a pseudo forecasting manner in lieu of the more realistic inflow model data. Details may be obtained from the companion report, PWRRC Report #80.

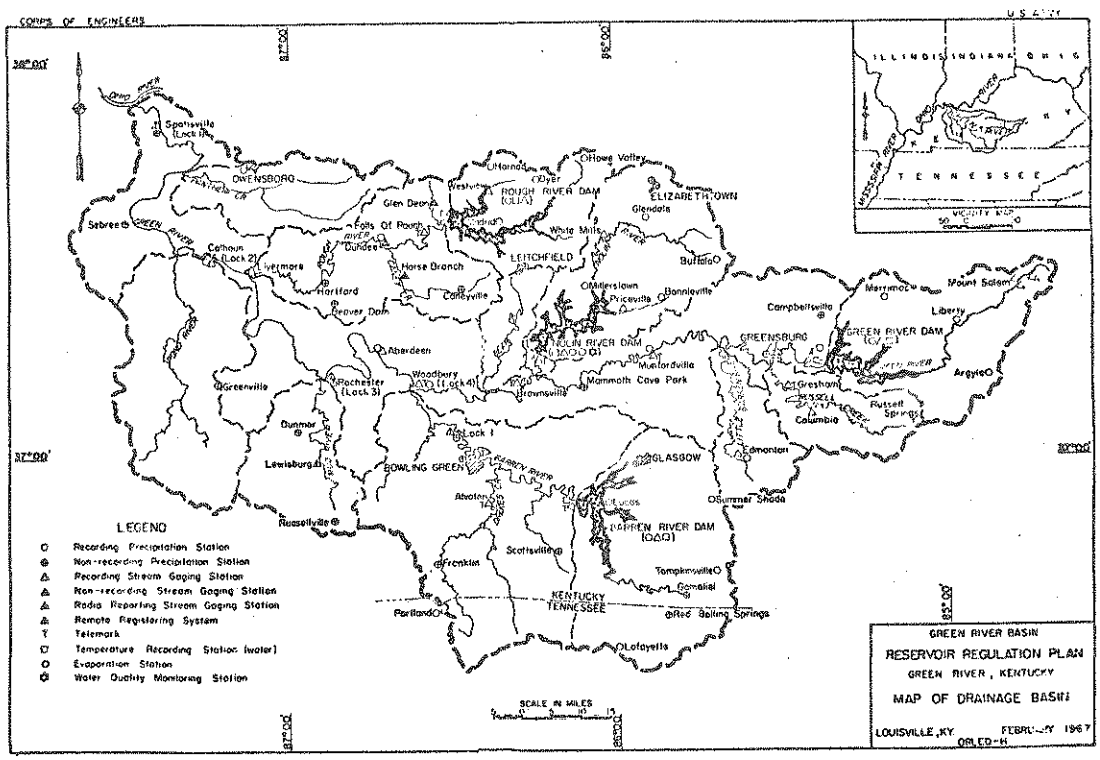


FIGURE III-1 - GREEN RIVER BASIN WATERSHED AND RESERVOIRS

IV. RESERVOIR AND RESERVOIR SYSTEM REGULATION

In this chapter, the official "stated" regulation plans for each of the Green River Basin Reservoirs are discussed as they have been understood for the purposes of the research reported herein. The discussion, i.e. the researchers' understanding and interpretation of the collected materials, has been divided into two parts. In the Sections IV-1, 2, and 3 the design of reservoir regulation plans by the Corps of Engineers are discussed in a general way. This was done so as to facilitate a review of the information that pertains specifically to the Green River Basin, Kentucky. The discussion of reservoir regulation information for the GRB is found in Sections IV-4, 5, 6.

1. DESIGN OF REGULATION PLANS

The objective of drawing up a reservoir regulation plan is to ensure the use of scientific principles in the regulation of a reservoir. The regulation purpose is to obtain optimal benefits from the reservoir. The regulation plan is necessarily drawn up as part of original design and authorization documents. Often revisions are made during later operations since not all practical problems can be foreseen, not all local stages can be computed with accuracy, etc.

The manner in which regulation plans are developed follows steps discussed and recommended in the Manual EM 1110-2-3600, Corps of Engineers, U.S. Army, 1959. The regulation plan information is developed from the study of mass curves as well as the study of representative historical hydrologic events. These studies amount to the simulation of reservoir regulation using historic data.

They involve the use of rainfall-runoff and routing models. Much of the methodology was developed in pre-computer days. Typical steps involved in designing a regulation plan as these can be interpreted from the manual, are shown in Fig. IV-1.

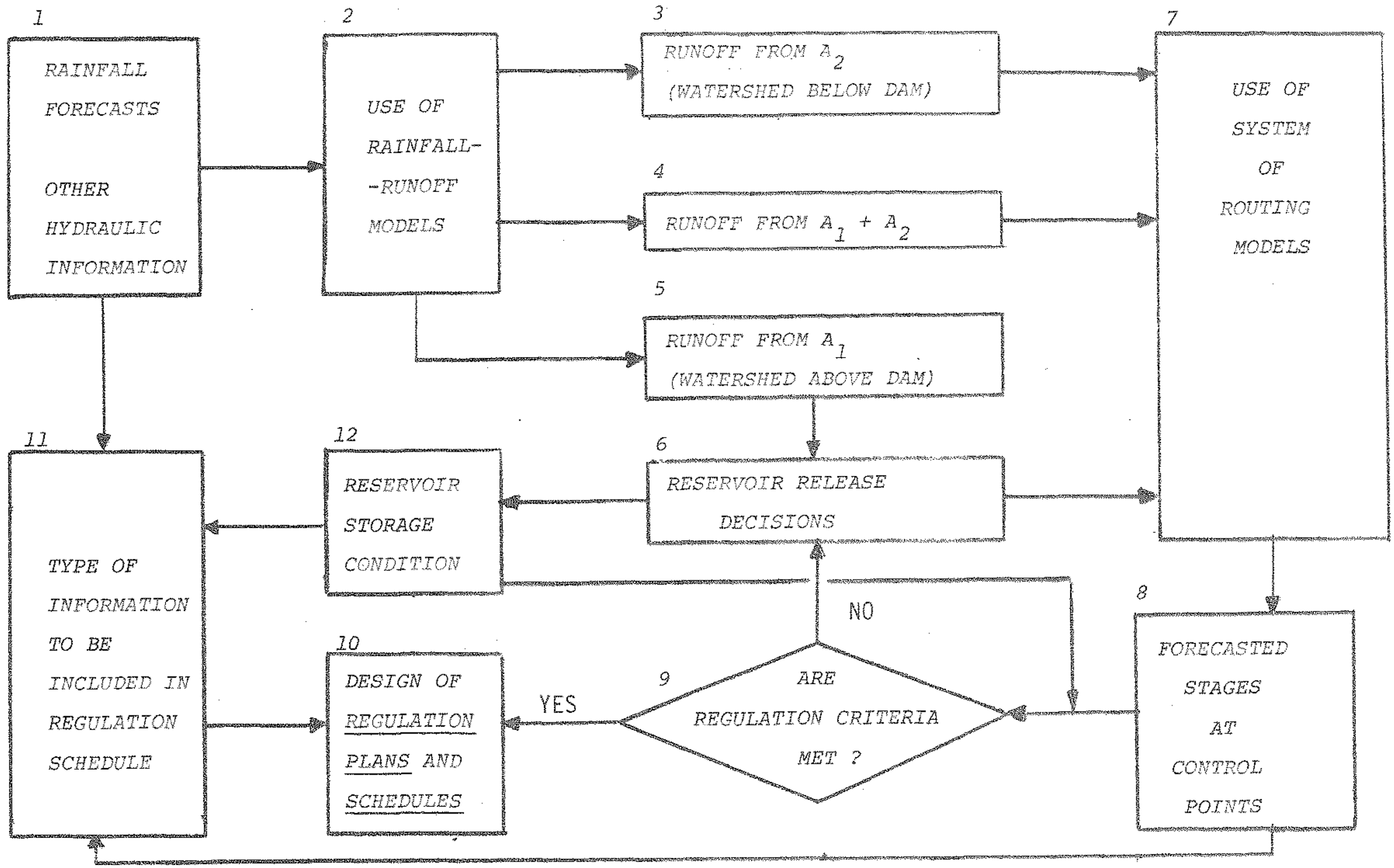


FIGURE IV-1 - STEPS INVOLVED IN DESIGNING A REGULATION PLAN AND INFORMATION TO BE INCLUDED IN A REGULATION SCHEDULE. IN SIMULATION STUDIES OF TO BE DESIGNED REGULATION SCHEDULES THE CRITERIA INVOLVE COMPARISONS OF BEFORE ($2 \rightarrow 4 \rightarrow 7$) AND AFTER CONDITIONS ($2 \rightarrow 3$, $5 \rightarrow 7$).

NOTE: this graph represents an interpretation of material found in the COE Manual EM 1110-2-3600 (1959)

2. WATER CONTROL CHARTS

Regulation decisions do depend on more factors than can be shown in a regulation schedule. For example, the travel time of flood wave is one of the considerations involved during critical periods of flood control operation. The travel times between reservoir outlets and control stations can be read from so-called Water Control Charts. A sample of a Water Control Chart is shown in Figure IV-2. The sample is for Muskingum River Basin. A similar chart exists for the Green River Basin (see PWRRC Report #80).

Water Control Charts also provide a convenient way to display the results and expected results of reservoir regulation. There are spaces to display reservoir elevations, control stages, and their relationships. Such charts were developed largely during pre-computer day. They have the advantage of characterizing many of the essential elements of the reservoir regulation problems.

If one were to converge current reservoir regulation methods to methods that would be "computer-assisted" to the greatest possible extent, one could imagine the numerical outputs to be sufficient for making a next reservoir release decisions. Even then, however, their recording of computer simulation model outputs on a Water Control Chart would remain a valuable presentation mode.

Nevertheless, the availability of computer simulation program and, in general, information processing speed and capability make that Water Control Charts represent unincreasingly narrow focus. For example, the uncontrolled side inflow and the factor on which it can be expected to depend at any one instance during the reservoir regulations, can not be shown. Yet one more disadvantage, however, is the fact that one can not conveniently show sets of predicted reservoir elevations and control stages as a function of various sets of expected parameter values and potential release decisions. Using a computer, one can, of course, arrange simulated outputs in any one way that is desired and for any number of trial parameter values and release decisions.

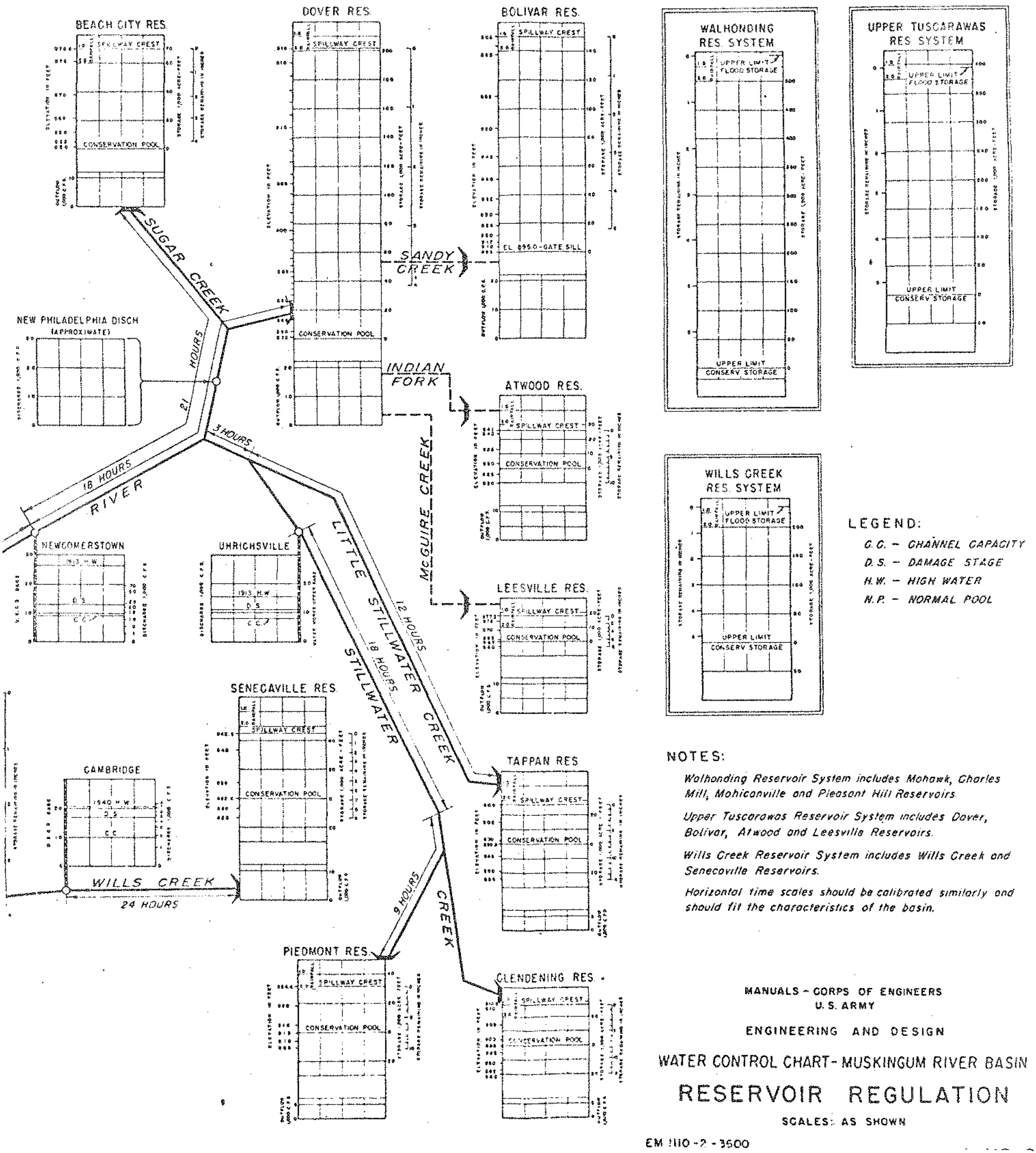


FIGURE IV-2 - PORTION OF A WATER CONTROL CHART

3. *REGULATION SCHEDULES*

A regulation plan reflects all the details obtained during the design studies referred to in Figure IV-1. In order to summarize this information, so-called regulation schedules are drawn up. A regulation schedule is a one or two page summary statement that shows for a given reservoir:

(a) Guide curve or rule curve and sometimes certain operating zones in the rule curve diagram;

(b) Regulation schedules; and

(c) Constraints.

The rule curve is a statement that specifies how, in the average, reservoir storage is to be used at any one time of the year. A graphical representation of this average, expected, as well as recommended storage used is a part of a typical regulation schedule such as the one shown in Figure IV-3. The rule curve in essence represents the "long-run" operation goals for a reservoir.

During a major flood or drought reservoir level will necessarily deviate from the rule curve. The reservoir regulation procedures that are designed to return the reservoir elevation to the rule curve level may be called "short-run" regulation procedures. These are broken down in a number of regulation schedules. The regulation schedules are specified as a set of conditionals involving the current stages at control stations, current reservoir elevation and time of the year (see Figure IV-3).

Finally the overall regulation schedule shows various constraints on the release decision.

In the study reported herein, four regulation shcedules, one for each of the four GRB reservoirs, were initially used to construct a simulation algorithm for reservoir operation. In other words, the regulation schedules were interpreted as "stated operating policies" reflective of original reservoir (system) design objectives.

TABLE 6

ROUGH RIVER RESERVOIR

SCHEDULE OF REGULATION

FLOOD CONTROL AND LOW FLOW REGULATION

Schedule	Controlling Stages (feet) Ohio River Evansville	Green River Lock 2, Upper Gage	Green River Lock 4, Upper Gage	Range in Pool Elevation (feet)	Time of Year	Regulation
	(All stages must exist)					
A	Below 37 or Below 46F	Below 19 or Below 29F	Below 17 or Below 22F	Minimum Pool, 465	1 December - 14 March	Release inflow necessary to maintain pool, provided release indicated in Maximum Release table is not exceeded.
B	Same as in Schedule A			465.0 - Spillway Crest (524)	1 December - 14 March	Release at rate indicated in Maximum Release table.
					15 March - 30 November	Maintain pool as near rule curve as possible while meeting minimum flow and flood control requirements.
	(Any one condition to exist for application of Schedule C)					
C	At or above 37R or 3 days before 42	At or above 19R or 2 days before 23	At or above 17R	465 - 514	1 December - 14 March 15 March - 30 November	Release at a constant rate of 100 c.f.s. Release at a constant rate of 100 c.f.s. when pool is at or above elevations prescribed by Rule Curve. When below elevation prescribed by rule curve release only the minimum requirement of 50 c.f.s.
D	Same as Schedule C			514 - 524	All year	When precipitation forecasts indicate need to retain storage capacity for local Rough River control, pass inflow only, up to a rate indicated in Maximum Release table. However, unless a regulation based on such a forecast can prevent significant damages in Rough River, regulate so as not to increase flood crests on Green or Ohio Rivers, subject only to releasing at a minimum rate of 100 c.f.s.
E	Control stations no longer considered			At 524 and above	All year	Release inflow up to capacity of conduit. If pool exceeds elevation 524 keep conduit open until pool returns to elevation 524. Maintain pool at elevation 524 by passing inflow until downstream conditions permit return to Schedule B. (At such a time, the Reservoir Regulation Section will evaluate weather and river conditions to determine feasibility of releasing on recession of downstream stages to regain storage capacity for possible storm recurrence.)

MAXIMUM RELEASE

Combined Flow Glen Dean and Horse Branch c.f.s.	Allowable Release c.f.s.*
Below 100	3,000
100-200	2,800
200-300	2,500
300-500	2,100
500-800	1,700
800-1,000	1,400
1,000-1,200	1,000
1,200-1,400	700
1,400-1,600	300
Above 1,600	100

* Subject to limiting stage of 20 feet at Dundee

MINIMUM LOW FLOW RELEASE

50 c.f.s.

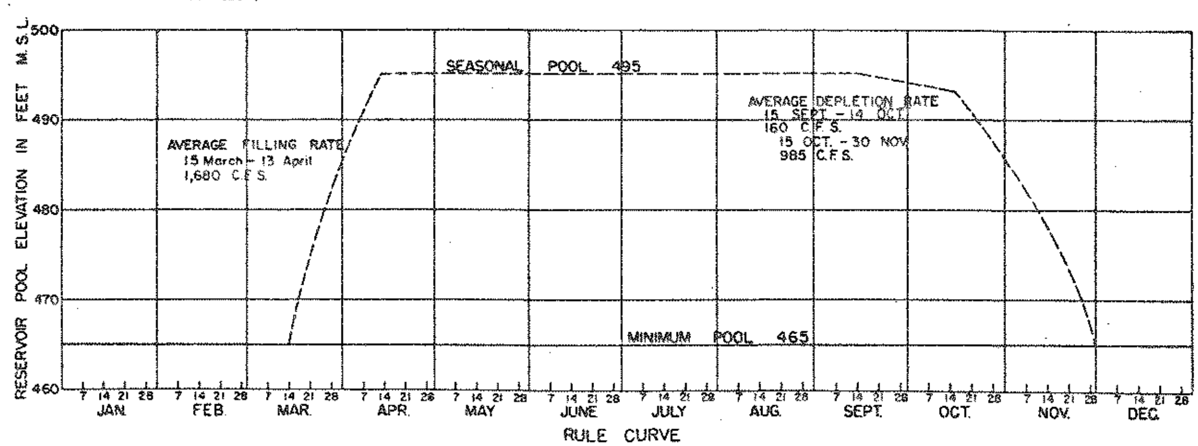


FIGURE IV-3 - SAMPLE REGULATION SCHEDULE SHOWING RULE CURVE, SEVERAL SUB-SCHEDULES, AND CONSTRAINTS

4. REGULATION PLAN FOR GREEN RIVER BASIN

The regulation plan (Master Manual) for the Green River Basin was completed in 1967. It has four appendices; each appendix described a regulation plan for an individual reservoir.

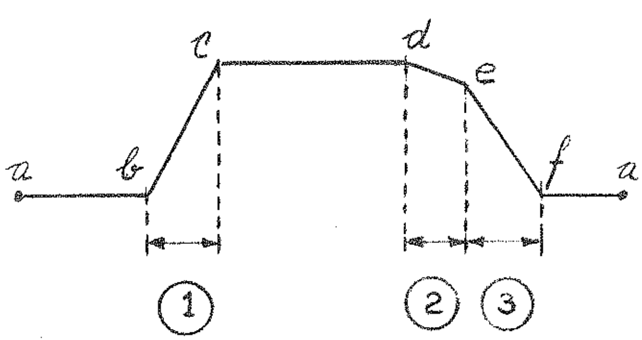
The GRB reservoir system was built in stages. The reservoir completion dates were as followed:

Rough (1960), Nolin (1963)
Barren (1964), Green (1969)

The primary objective of the proposed regulation plan for the GRB system was flood control. A secondary objective was recreation. Storages in the four reservoirs are large to very large. They amount to 4.5 inches of runoff for the entire GRB watershed and up to between 14" and 20" for the reservoir-controlled watersheds (see PWRRC Report #80, II-1). Because of the large storage capacity, flood control regulation is occasionally demanded by interests as far downstream as the lower Mississippi even though this is not shown as part of the regulation schedules. During the past decade, a number of additional regulation objectives have gained in importance. This aspect is discussed further in section VII-6.

5. GRB REGULATION SCHEDULES

The regulation plan for the Green River Basin has been decomposed into four regulation schedules, one for each of the GRB reservoirs. The most characteristic element of each schedule is the rule curve. A typical rule curve is shown in Figure IV-4.



Period	Action
1. Mar 15 - Apr 13	Filling
2. Sept 15 - Oct 14	Slow drawdown
3. Oct 15 - Nov 30	Drawdown

FIGURE IV-4 - TYPICAL SHAPE OF RULE CURVES FOR GRB RESERVOIRS

The typical regulation schedule for a given reservoir represents a guide for reservoir regulation that seems nearly independent of the guides for other reservoirs. They are coupled together only by three main control stations. The stages at gaging stations at Woodbury, Calhoun and Evansville are parts of each of the four regulation schedules.

Each regulation schedule involves one or two local control stations whose stages or flow rates define the reservoir release constraints. Also each regulation schedule provides for minimum release constraints.

In the regulation schedules, there is no explicit reference to the use of precipitation and/or runoff forecasts. For the Green River Reservoir, the separate water quality reservation is shown in the rule curve diagram. No corresponding release decision conditions or constraints are shown.

6. *IMPLEMENTATION OF RESERVOIR REGULATION*

The regulation plan also details how reservoir regulations are to be implemented. It specifies how various responsibilities are to be assigned. In principle, responsibility is delegated as much as possible. Only during severe flood conditions or very special circumstances will the entire line of commands be involved in regulation. This line of commands is as follows:

* Division Office at Cincinnati, Ohio - General supervision; regulation involvement during extreme flood or special circumstances only.
* District Office at Louisville, Kentucky - Supervision of Divisions charge with regulation responsibility.
* Engineering Division and Operation Division - Supervision of branches and sections with regulation responsibility.
* Hydraulic Branch, Reservoir Regulation and Hydrologic Data Section - data collection from stations and from other agencies (NWS, USGS), formulate and relay regulation instructions to Reservoir Branch, improve regulation techniques, etc.
* Reservoir Branch and Maintenance Branch with Communications Sections - relay regulation instructions to Dam Tenders, transmit Dam Tender Reports, etc.

* Reservoir Manager, Dam Tender - actual management of reservoir, outlet works and other facilities.

The above Division responsibility appears to reflect a military organization structure designed to bring management resources into actions in proportion to the severity of a regulation problem. This implies discontinuous integration may impede operating policy adaptation.

V. DEVELOPMENT OF OPERATING POLICY SIMULATION MODEL

The development of reservoir regulation schedules has been discussed in Chapter IV. By way of illustration, one of the four regulation schedules (namely, the R.S. for Rough River Reservoir) was shown earlier in Figure IV-3.

Initially an attempt was made to translate the regulation schedules directly and as literally as possible into an algorithm called "reservoir operating policy." This was found to be insufficiently representative of actual field operations. The necessary modifications and further refinements of the operating policy algorithms (one for each reservoir) led to the need to rearrange and to re-interpret the official regulation schedules. This matter is discussed in Chapter V below.

1. *SYSTEMS GRAPHS OF REGULATION SCHEDULES*

Before going into the rearrangement and interpretation of official operating schedules, for the purpose of "algorithmizing" it, it is best to first illustrate their structure. This is done by means of Figure V-1. Although Figure V-1 pertains to the Rough River Reservoir, it is quite representative for regulation schedules of the other three reservoirs.

Figure V-1 shows that releases from the Rough River Reservoir are made in accord with the RRR regulation schedules. As discussed in Sections IV-3, 4, and 5, the typical regulation schedule reflects the long-run objectives by means of a rule curve. The short-run objectives are pursued by prescribing constraints and release schedules (see Figure V-1, Block 4). These specifications are only part of the input to the reservoir regulation process. In addition, a number of dynamic variables are needed. Among these are the reservoir surface elevation (1 → 3, Figure V-1), the discharges or stages for local gaging stations (5, 6, 7 → 3), and the stages for stream reaches that are influenced not only by RRR releases, but also by releases from other storages (8, 9, 10 → 3).

Systems graphs similar to Figure V-1 for the other GRB are found in PWRRC #80.

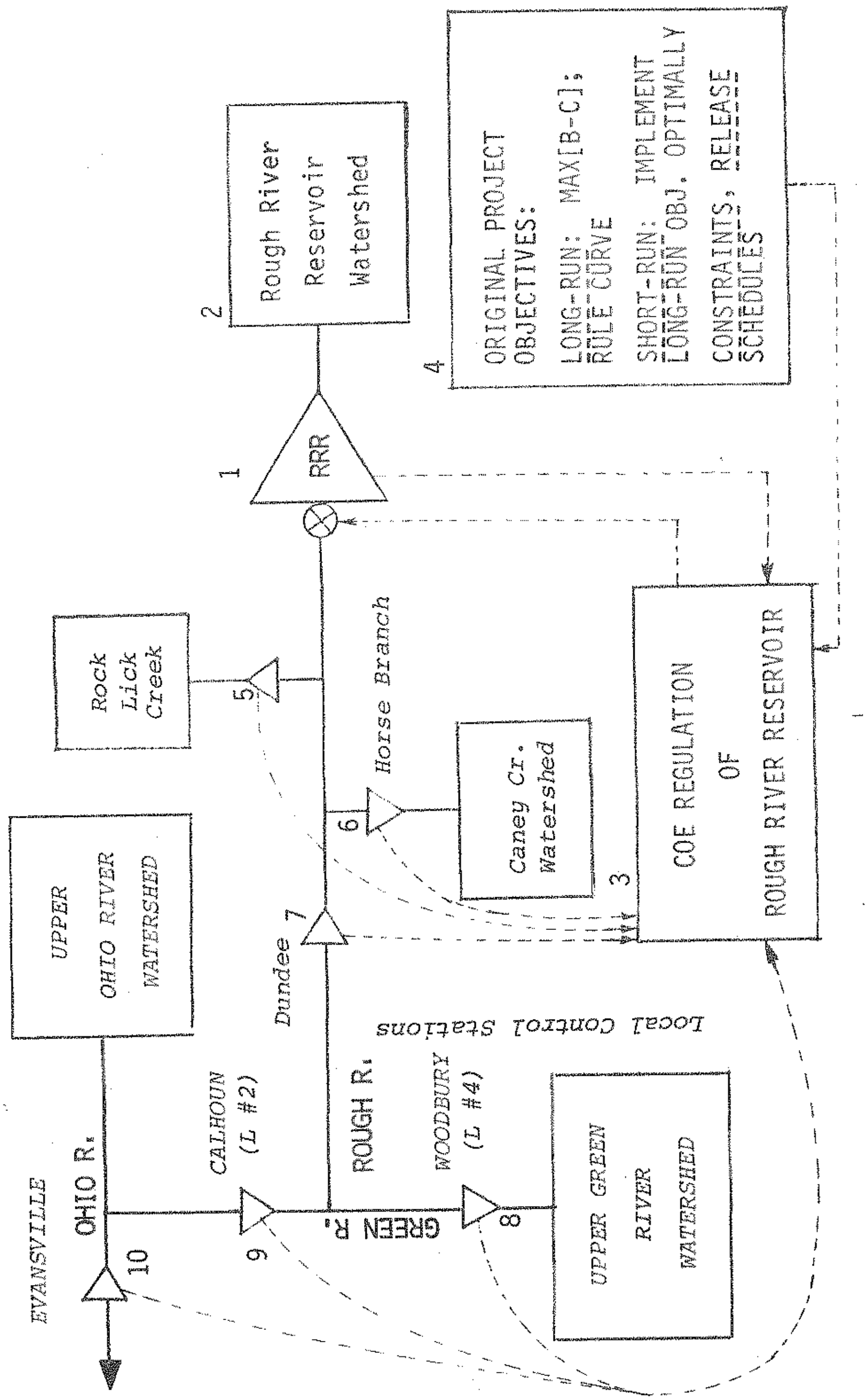


FIGURE V-1 - A SYSTEMS GRAPH FOR THE REGULATION SCHEDULE OF ROUGH RIVER RESERVOIR. THE ROLE OF THE TIME OF YEAR IS NOT PORTRAYED IN THIS GRAPH.

The locations whose stage and/or discharge information is called for in the regulation schedules, are called "control stations." The stations 5, 6, and 7 are local controls; the staitons 8, 9 and 10 are system controls. The variable values collected at controls are commonly called "system state parameters." This term is clarified by means of Figure V-2. It shows how the stations 8, 9 and 10 tie together the regulation of the four GRB reservoirs.

2. *REGULATION AND INTERPRETATION OF REGULATION SCHEDULES*

In practice, the regulation schedules are to a greater or lesser extent "guides for regulation." They require further interpretation, the addition of "rules of practice," and the taking into account of information that is relevant at any one moment. For the purposes of translating the regulation schedules into operating policy algorithms, a further interpretation had to be adopted for each of them. Taking the Nolin Reservoir Regulation Schedule, Figure V-3, as an example, this interpretation is shown in Figures V-4 and V-5.

Figure V-4 portrays the relationship between:

(a) five classes of reservoir releases decision (vertical columns) and their relation to rule curve information,

(b) reservoir state in the form of surface elevation, and

(c) system constraints in the form of channel controls.

Figure V-3 represents the first step in ensuring completeness and consistency of an algorithmic regulation schedule. The resulting A, B, C, D and E classes differes somewhat from the A, B, C, D and E classes that are part of the official regulation schedules. The extent of the differences indicates some incompleteness or inconsistency of the offical regulation schedules when they are regarded algorithmically.

Figure V-5 shows a further interpretation of the Nolin River Reservoir regulation schedules. The A, B, C, D and E release classes of Figure V-4 have been provided with further detailed specifications. The results have been made to agree as much as possible to the specifications shown or implied in the official regulation schedule for the Nolin River Reservoir.

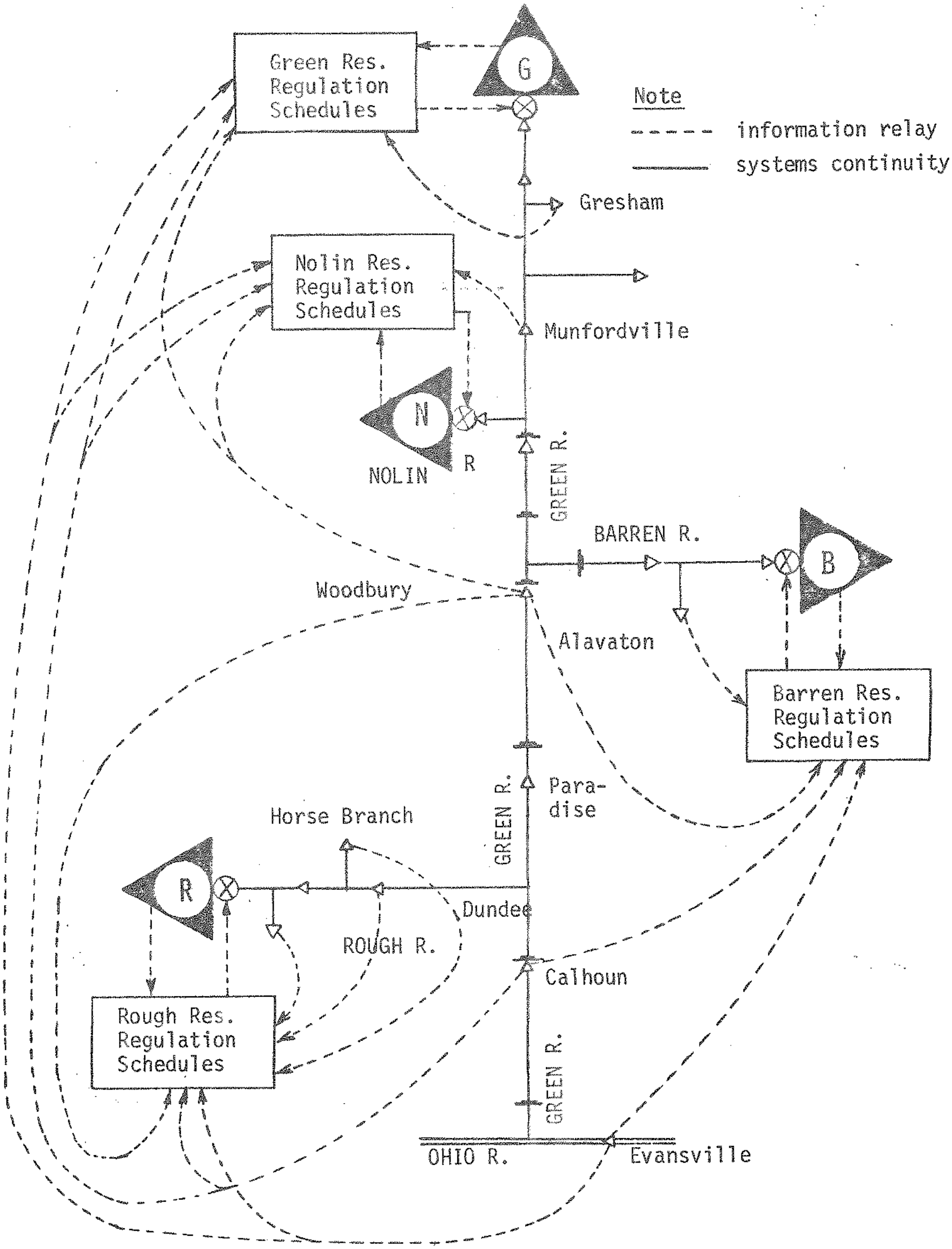


FIGURE V-2 - SYSTEMS STATE INFORMATION USED IN GREEN RIVER BASIN REGULATION

TABLE 6

NOLIN RIVER RESERVOIR

SCHEDULE OF REGULATION

FLOOD CONTROL AND LOW FLOW REGULATION

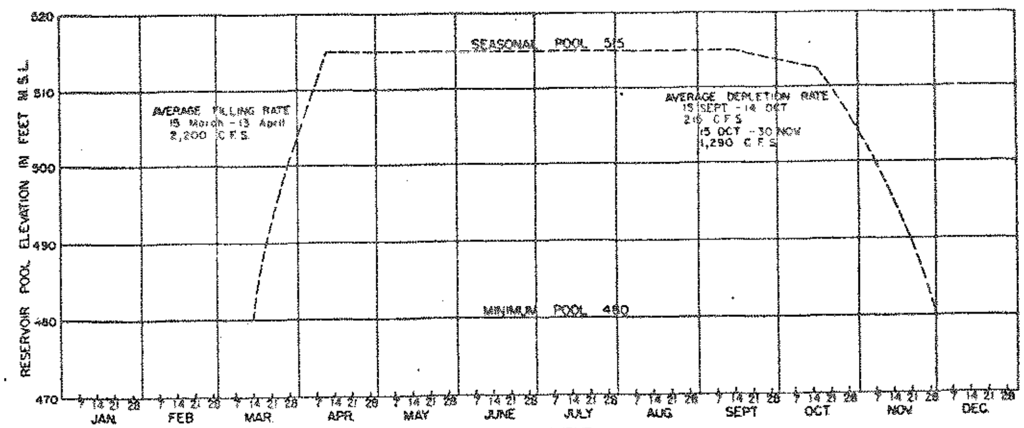
Schedule	Controlling Stages (feet): Ohio River Evansville	Green River Lock 2, Upper Gage	Green River Lock 4, Upper Gage	Range in Pool Elevation (feet)	Time of Year	Regulation
	(All stages must exist)					
A	Below 37 or Below 46F	Below 19 or Below 29F	Below 17 or Below 22F	Minimum Pool, 480	1 December - 14 March	Release inflow necessary to maintain pool, provided release indicated in Maximum Release table is not exceeded.
B	Same as Schedule A			480 - Spillway Crest (560)	1 December - 14 March	Release at rate indicated in Maximum Release table.
					15 March - 30 November	Maintain pool as near Rule Curve as possible while meeting minimum flow and flood control requirements.
	(Any one condition to exist for application of Schedule C)					
C	At or above 37R or 3 days before 42	At or above 19R or 4 days before 23	At or above 17R	480 - 550	1 December - 14 March 15 March - 30 November	Release at a constant rate of 300 c.f.s. Release at a constant rate of 300 c.f.s. when pool is at or above elevations prescribed by Rule Curve. When below elevation prescribed by Rule Curve, release only the minimum requirement of 50 c.f.s.
D	Same as Schedule C			550 - 560	All year	Release all inflow provided release indicated in Maximum Release table is not exceeded and outflows are never reduced to less than 300 c.f.s.
E	Control stations no longer considered			At 560 and above	All year	Release inflow up to capacity of conduit. If pool exceeds elevation 560 keep conduit open until pool returns to elevation 560. Maintain pool at elevation 560 by passing inflow until downstream conditions permit return to Schedule B. (At such times, the Reservoir Regulation Section will evaluate weather and river conditions to determine feasibility of releasing on recession of downstream stages to regain storage capacity for possible storm recurrence.)

MAXIMUM RELEASE

Munfordville Stage (feet)	Release (c.f.s.)
Below 20.0	10,000
20.0 - 22.0	8,000
22.0 - 24.0	6,100
24.0 - 26.0	4,200
26.0 - 28.0	2,100
Above 28.0	300

MINIMUM LOW FLOW RELEASE

50 c.f.s.



RULE CURVE

FIGURE V-3 - OFFICIAL NOLIN RESERVOIR REGULATION SCHEDULE

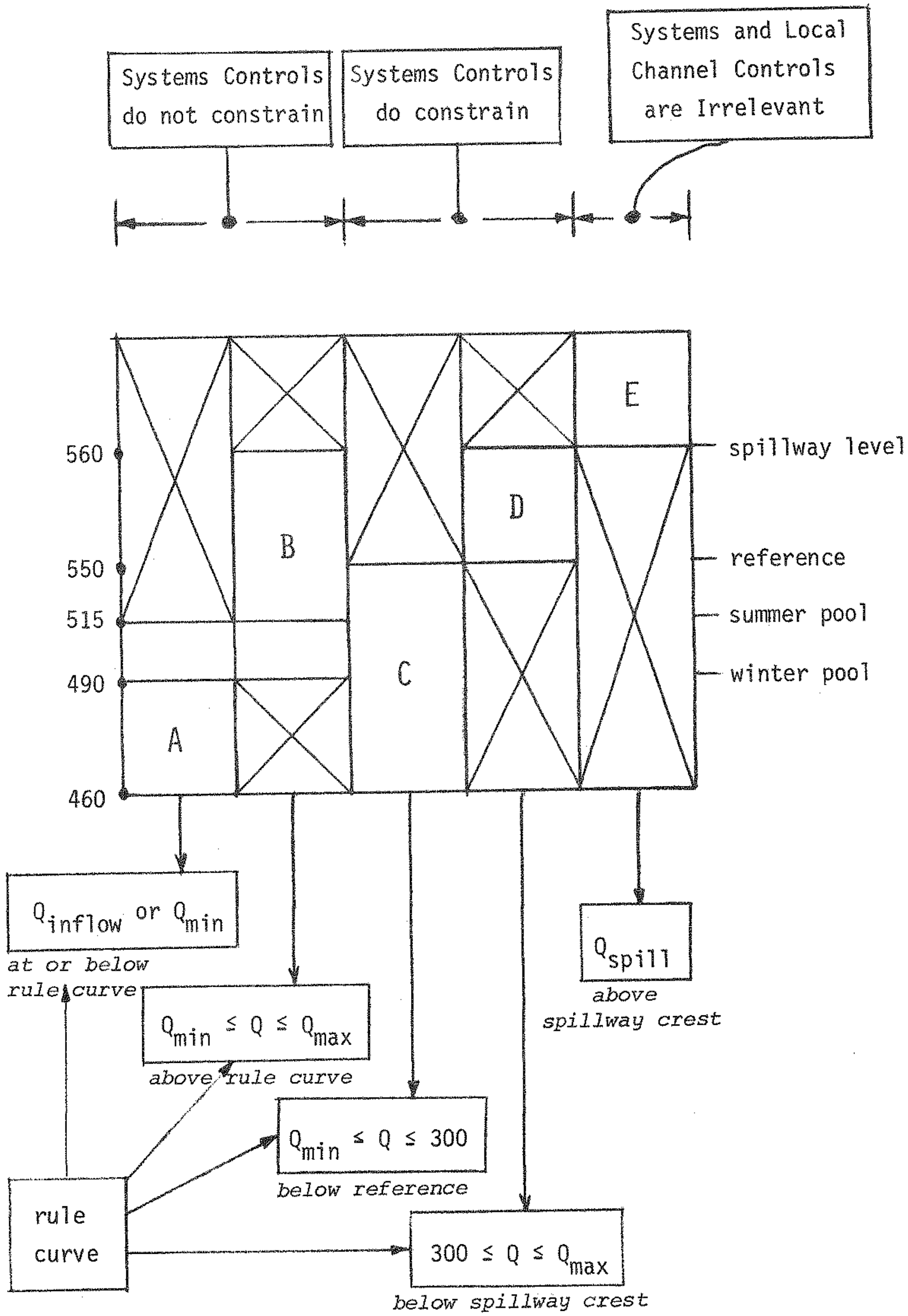


FIGURE V-4 - INTERPRETATION OF THE REGULATION SCHEDULE OF NOLIN RESERVOIR AS A FIRST STEP IN ALGORITHMIZING A STATED SCHEDULES

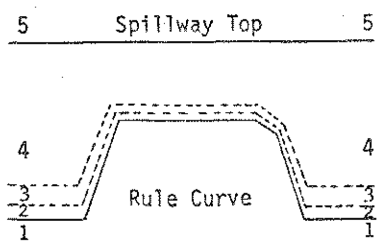
PLAN	CONTROLLING STAGES (FEET) OHIO RIVER EVANSVILLE	GREEN RIVER CALHOUN	GREEN RIVER WOODBURY	POOL ELEVATION ZONE	SCHEDULE FROM FIGURE V-4	SPECIFICATION OF REGULATION
1	Control Station no longer considered			Zone 5 (Above spillway crest)	E	Release the conduit capacity.
2	[Below 37 or Below 46F] and	[Below 19 or Below 29F] and	[Below 17 or Below 22F]	Zone 1 (Below rule curve)	A	Release Q_{min}.
				Zone 2 (At rule curve)	A	Release inflow but not less than Q_{min}.
				Zone 3 (Slightly above)	B	Release $Q_{r,t}$ so as to lower pool to guide curve level in 1.0 day.
				Zone 4	B	Release $Q_{r,t}$ so as to lower pool to guide curve with the lowering rate of 0.4 ft/day (summer), 1.0 ft/day (winter) or 3.0 ft/day if elevation more than 2.5 ft. above guide curve and falling. If falling and storage being evacuated on the previous day, keep the same gate opened. In any case, the Q_{max} must not be exceeded.
3	[Above 37R or Above 46] or	[Above 19R or Above 29] or	[Above 17R or Above 22]	Zone 1	C	Release Q_{min}
	or [Above 46 or Above 42R during 5 days]	or [Above 29 or Above 23R during 4 days]	or [Above 22 during 3 days]	Zone 2	C	Release inflow but not less than Q_{min}.
				Zone 3	C	Release $Q_{r,t}$ so as to lower pool to guide curve level in 1.0 day.
				Zone 4 (Rising)	C,D	Release Q_{hold}
				Zone 4 (Falling)	C,D	Release $Q_{r,t}$ so as to lower pool to guide curve with the lowering rate of 0.4 ft/day (summer), 1.0 ft/day (winter) or 3.0 ft/day if elevation more than 2.5 ft. above guide curve and falling. If falling and storage being evacuated on the previous day, keep the same gate opened. In any case, the Q_{max} must not be exceeded.

FIGURE V-5 - TYPICAL SPECIFICATION OF THE OPERATING POLICY RULES THAT ARE PART OF THE ALGORITHM USED TO GENERATE OPERATING POLICY RELEASE SERIES Q(t). THE SPECIFICATION SHOWN ABOVE IS FOR NOLIN RESERVOIR. IT IS TWO STEPS REMOVED FROM THE OFFICIAL COE REGULATION SCHEDULE (FIG V-4 IS ONE STEP REMOVED).

As an example of interpretation, the official regulation schedule statement:

"at or above 37R or 5 days before 42" (V-1)

has been given Figure V-5 interpretation of:

"the present day stage $\geq$ *37 rising* (V-2)
or 5^{th} *day ahead forecasting stage* $\geqslant$ *42"*

3. ALGORITHM DEVELOPMENT AND REFINEMENT

The rearrangements and interpretations just discussed (Section V-2) are not yet sufficient for constructing a reasonable algorithm. Figure V-6, for example, shows the result of a simulation run with an algorithm from an early project stage. The unrealistic oscillation in the outflow results from a "legalistic" conversion of the regulation schedule. While the official schedule calls, strictly speaking, for maximum releases whenever the reservoir level is above the rule curve, such a release pattern is not followed in practice. Rather, one unwritten operation criterion is to minimize variation of flow downstream of the dam. As a consequence, refinements of the algorithm are needed that lead to a damping of release variations.

A number of additional refinements were made and have been detailed in PWRRC Report #80. For example, Eq. V-2 dealing with anticipated stages at a control, has been refined. Also certain reductions of the prescribed maximum releases were built into the algorithms.

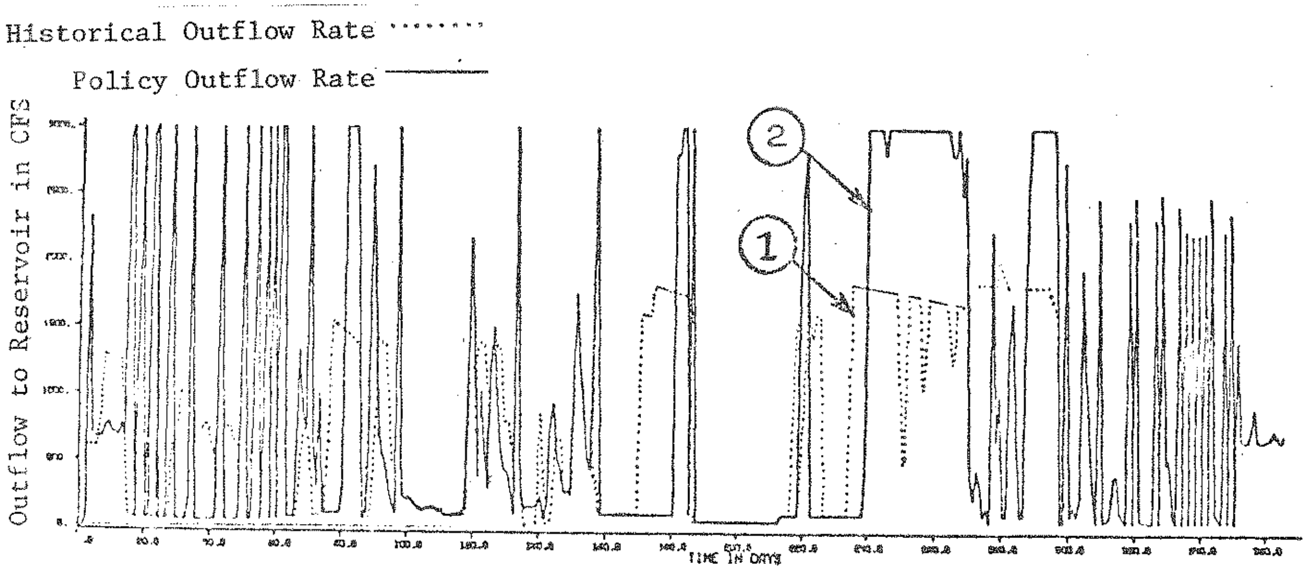


FIGURE V-6 - COMPARISON OF (1) HISTORIC RESERVOIR RELEASES AND (2) SIMULATED RESERVOIR RELEASES USING AN EARLY, LITTLE REFINED ALGORITHM. (FROM ROUGH RIVER RESERVOIR, KENTUCKY, W.Y. 1967)

4. NEEDED FURTHER REFINEMENTS

The constructed algorithms would not (yet) be suitable for actual field application. Several additions that are likely to be needed are the following:

(a) providing for rainfall forecasts to be among the algorithm's inputs;
(b) the use of reservoir inflow forecasting models;
(c) the use of side inflow forecast models;
(d) the use of river routing models to combine the four separate reservoir regulation algorithms into one system;
(e) routine release decision evaluation, in terms of variously weighted objectives, of a set of proposed release decisions;
(f) the involvement of mathematical programming in step (e) for the purpose of quickly identifying optimal release decisions.

VI. COMPARATIVE ANALYSIS OF HISTORIC AND SIMULATED RESERVOIR REGULATION DATA

The operating policy algorithm that was constructed as part of the project was used to generate for each of the GRB reservoirs a time series of "policy release" flows Q_t. The values of these time series have been compared with the historical releases as computed from the Dam Tender Reports (for RRR) or as measured at the gaging stations just downstream of the dams (for NRR, BRR, and GRR). In this chapter, the comparison between policy releases and historical releases is presented and analyzed.

1. *TYPICAL GRAPHICAL OUTPUT*

Output from the operating policy algorithm was obtained for the years and reservoirs shown in Figure VI-1. Figure VI-1 also shows for which years and which reservoirs (part of the) output has been shown in this report. They belong to group A and group B.

GROUP A

year / reservoir	1965	1966	1967	1968	1969	1970	1971	1972
Rough R. R.	X	X	X	X	X	X	X	
Nolin R. R.	X	X	X	X	X	X	X	X
Barren R. R.	X	X	X	X	X	X	X	
Green R. R.						X	X	X

GROUP B

FIGURE VI-1 - SUMMARY OF OPERATING POLICY SIMULATION OUTPUT. EACH X REPRESENTS A YEAR OF OUTPUT FROM THE OPERATING POLICY ALGORITHM.

OUTPUT GROUP A IS FOUND IN FIGURES VI-2, 4, 5, 6, and 7. OUTPUT GROUP B IS FOUND IN FIGURES VI-2, 8, 9, and 10. FIGURE VI-3 CONTAINS OPERATING POLICY DATA FOR ROUGH RIVER RESERVOIR FOR 1970, AND THIS RELATES TO FIGURE VI-2.

The Figures VI-2 thru VI-10 (except for Figure VI-3) are of the same type. The top of the figure shows the rule curve elevation for a particular year and a particular reservoir, together with the historical series of reservoir elevations. The historical reservoir elevation, together with the precipitation and river stage information, constitute inputs to the operating policy algorithm. In the lower half of the Figures VI-2 thru VI-10, the policy release outputs and the historical releases are compared on a day by day basis.

The Figure VI-2 pertains to the water year 1970 and to Rough River Reservoir. The Figure VI-3 provides the differences between policy release and historical release flow. The result is called "deviation series." The top half of Figure VI-3 records the rainfall distribution for the same period and the same reservoir. The deviation series and rainfall distributions were generated for all the 25 runs shown in Figure VI-1; because of their bulk they are not presented herein.

The Figure VI-2, 4, 5, 6, 7 (i.e. Group A in Figure VI-1) shows the reservoir elevations and flow releases for Rough River Reservoir for a group of five consecutive years. This group provides some impression of the variability in regulation results for a given reservoir.

The Figure VI-2, 8, 9, 10 (Group B) show the same information for all four reservoirs of the GRB system and for one particular year (1970). The Figures in group B permit one to see whether and how the operation of GRB reservoirs was integrated, i.e. to see a systems operation aspect (at least during the 1970 water year).

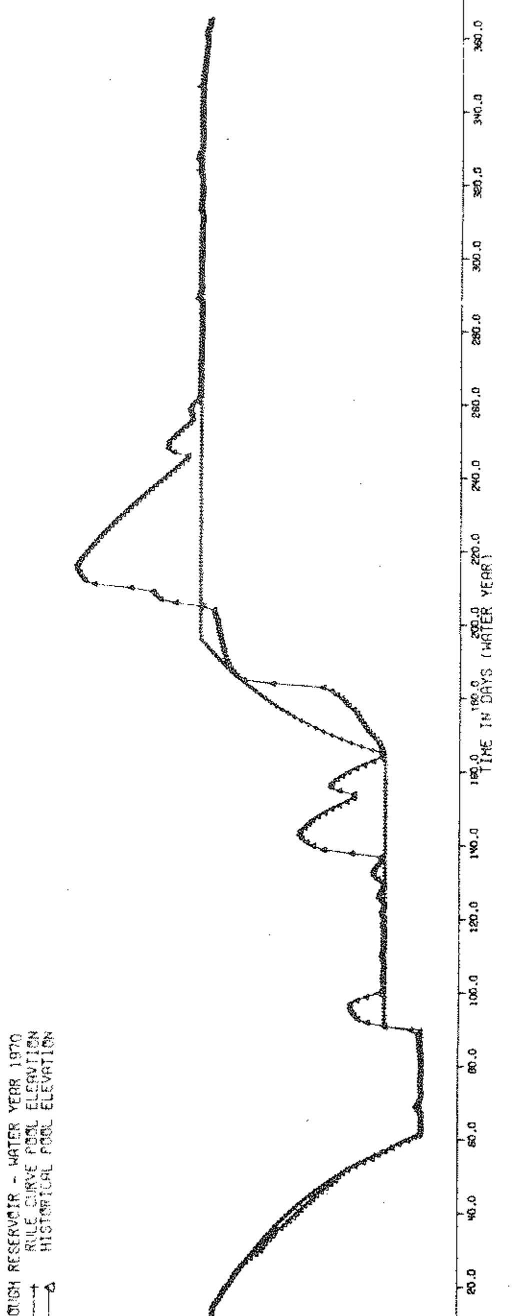


FIGURE VI-2-A - COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR

1 - Following guide rule curve closely, therefore no need for making big release for 1-2 days only

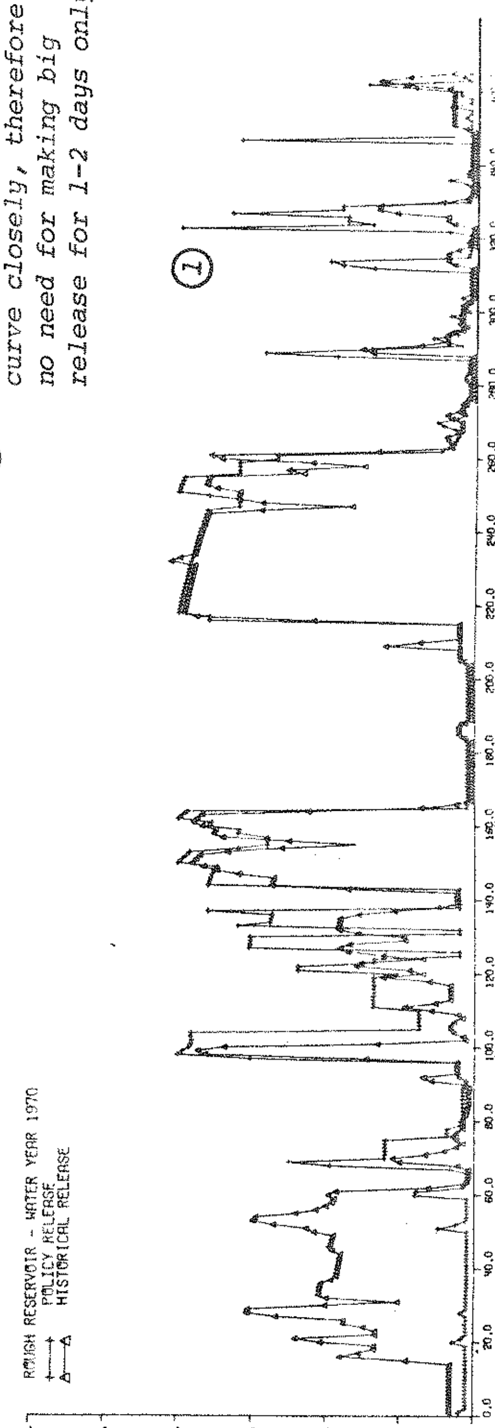


FIGURE VI-2-B - COMPARISON OF HISTORIC RESERVOIR RELEASES COMPUTED FROM DAM TENDER REPORT INFORMATION WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR.

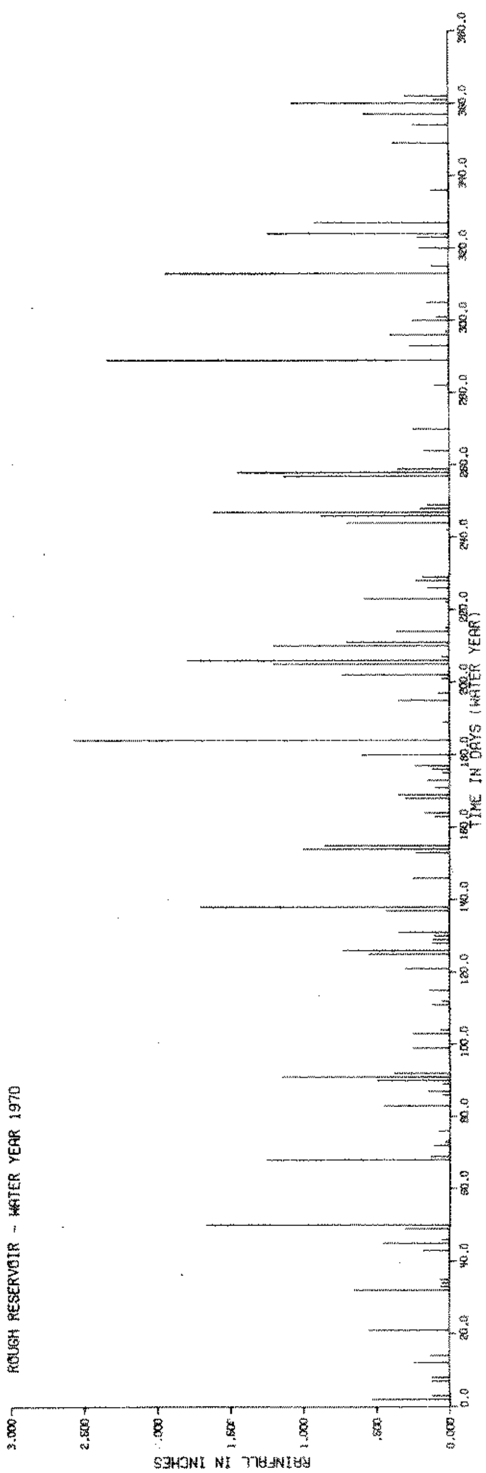


FIGURE VI-3-A - AVERAGE DAILY RAINFALL OVER THE ROUGH RIVER RESERVOIR WATERSHED

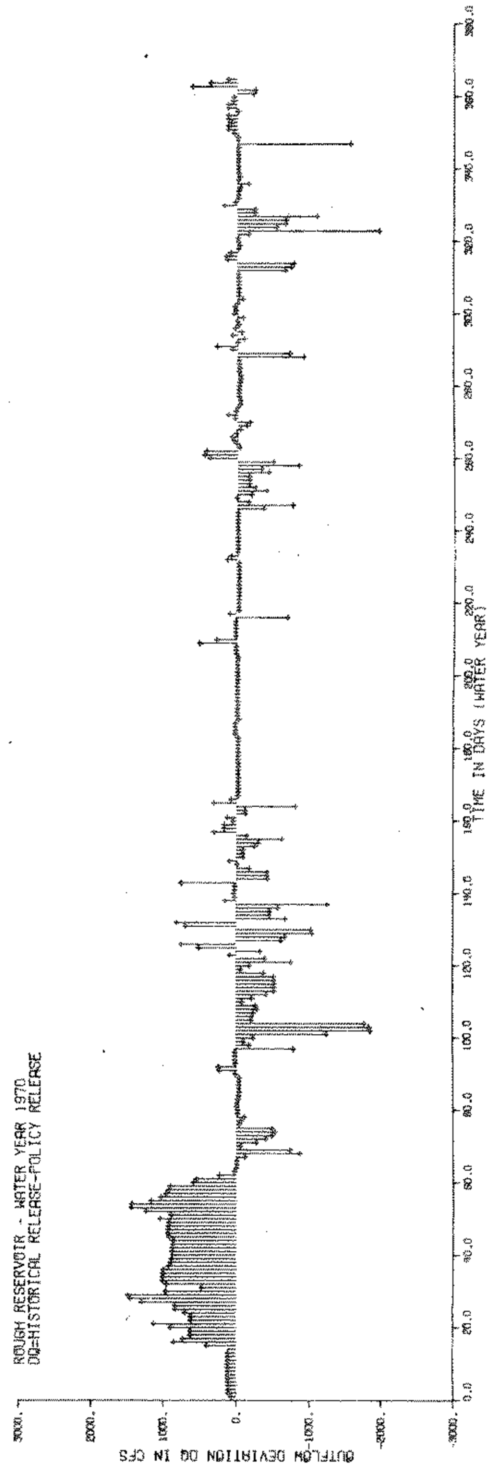


FIGURE VI-3-B - RESERVOIR RELEASE DEVIATION SERIES FOR ROUGH RIVER RESERVOIR, FOR THE 1970 WATER YEAR. THIS SERIES REPRESENTS THE DAY BY DAY DIFFERENCE BETWEEN HISTORICAL RELEASES COMPUTED FROM DAM TENDER REPORTS AND THE RELEASED OBTAINED FROM AN OPERATING POLICY SIMULATION MODEL. NOTE: THE DEVIATION DOES NOT SIGNIFY A CUMULATIVE EFFECT.

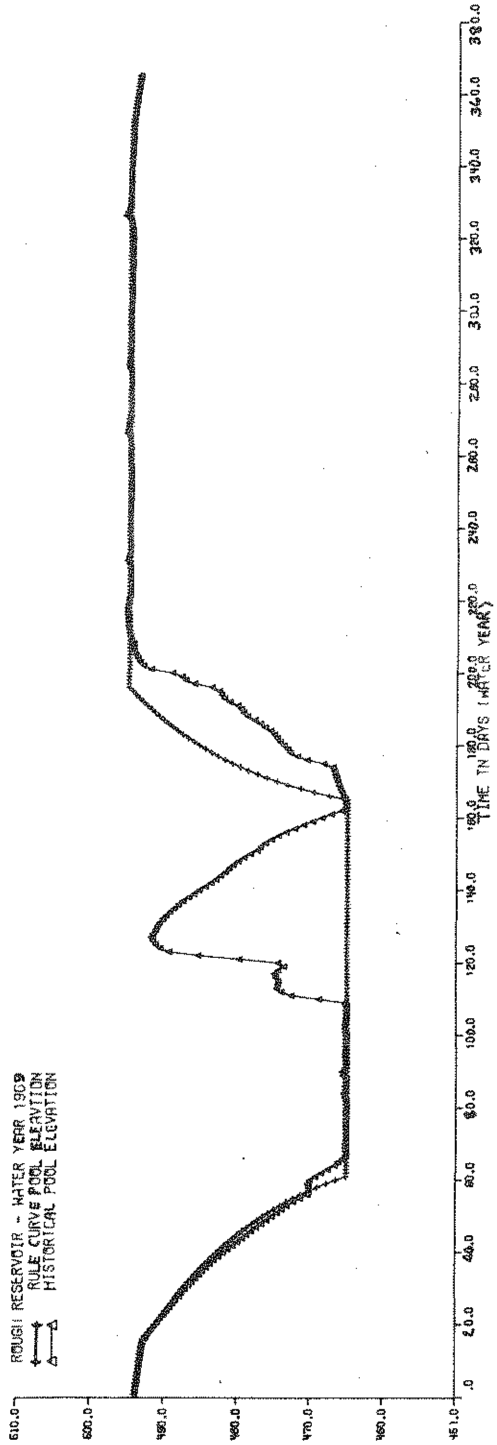


FIGURE VI-4-A - COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1969 WATER YEAR

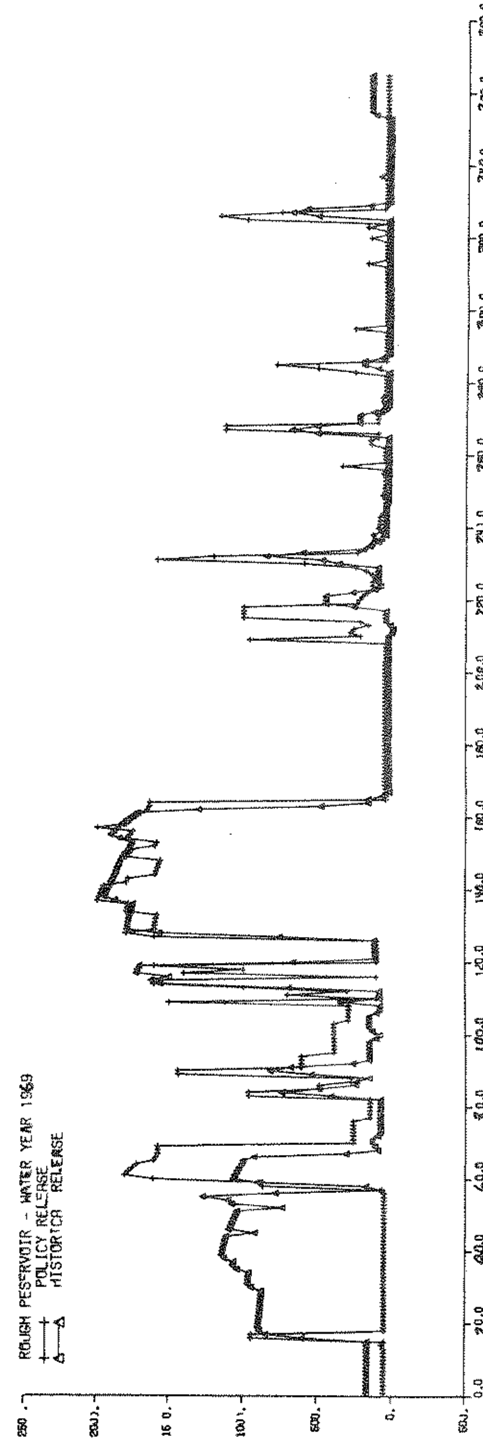


FIGURE VI-4-B - COMPARISON OF HISTORIC RESERVOIR RELEASES COMPUTED FROM DAM TENDER REPORT INFORMATION WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1969 WATER YEAR.

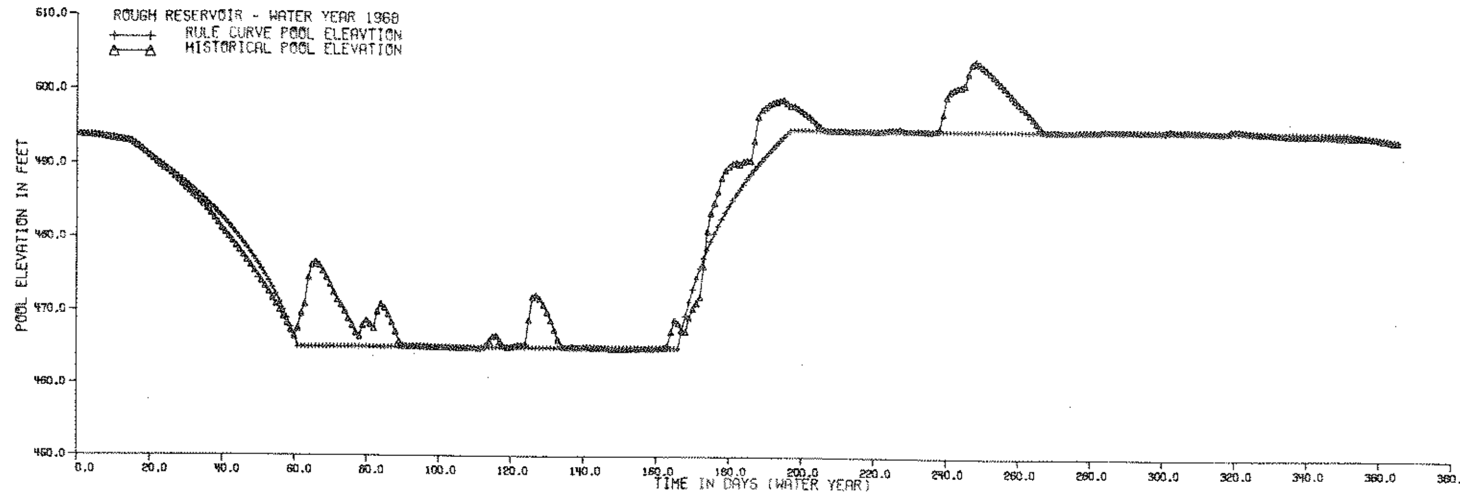


FIGURE VI-5-A - *COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1968 WATER YEAR*

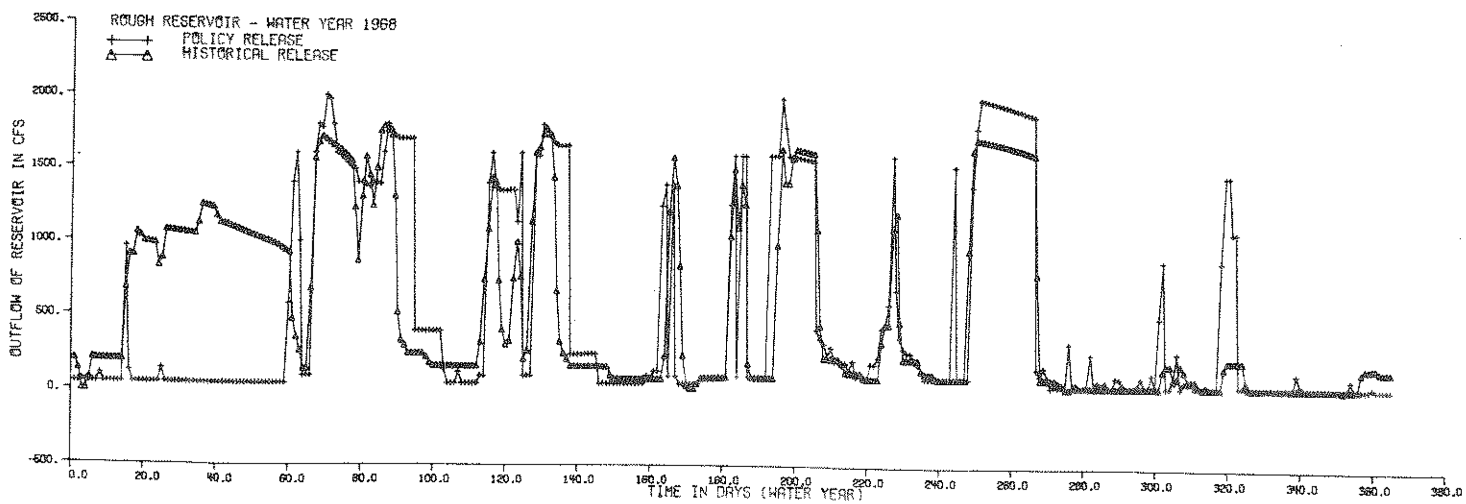


FIGURE VI-5-B - *COMPARISON OF HISTORIC RESERVOIR RELEASES COMPUTED FROM DAM TENDER REPORT INFORMATION WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1968 WATER YEAR.*

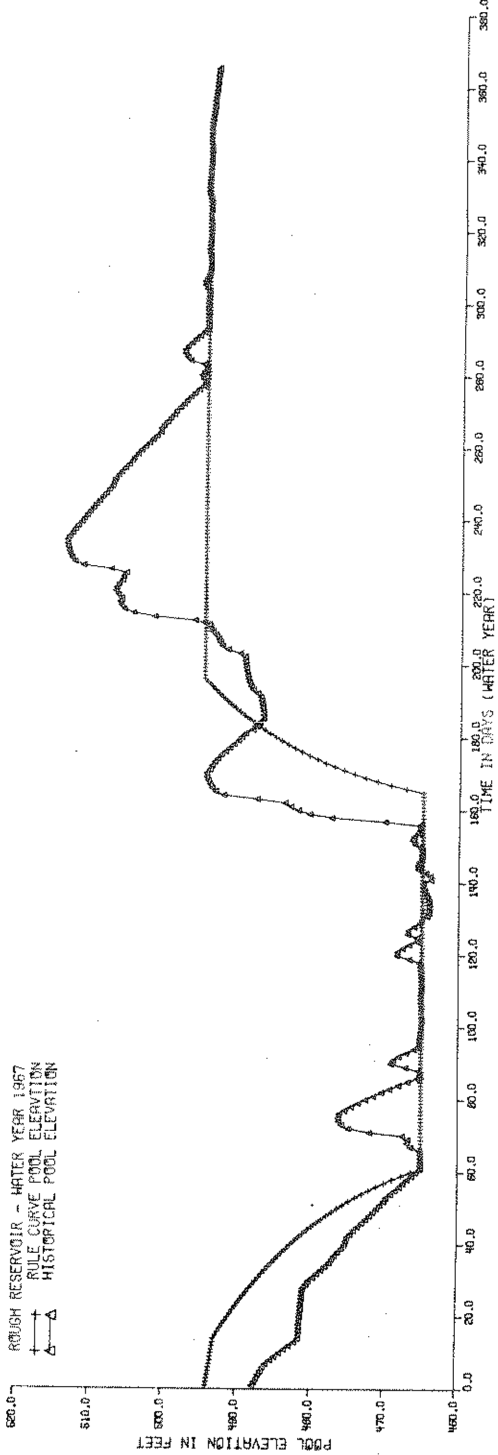


FIGURE VI-6-A - COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1967 WATER YEAR

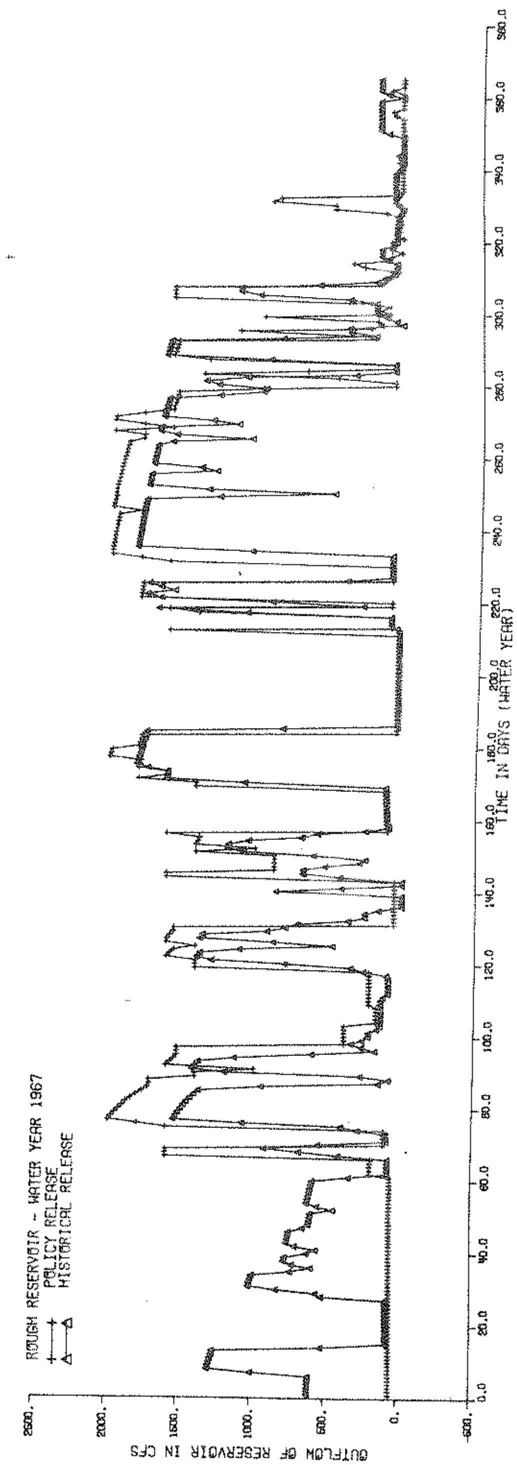


FIGURE VI-6-B - COMPARISON OF HISTORIC RESERVOIR RELEASES COMPUTED FROM DAM TENDER REPORT INFORMATION WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR ROUGH RIVER RESERVOIR, KY, FOR THE 1967 WATER YEAR

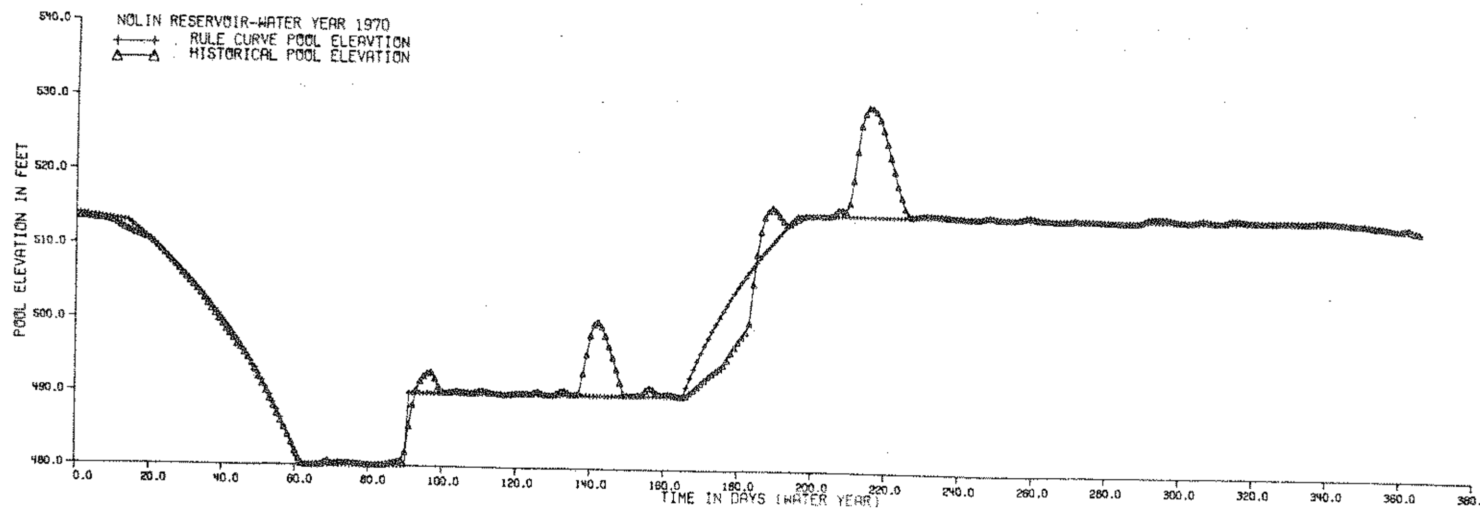


FIGURE VI-8-A - *COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR NOLIN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR*

① - *Release necessary to deplete summer pool*
② - *Regulation initiated 23 Dec. 69 to increase Minimum Pool Level from 480' to 490'*
③ - *Release less than policy to blend into guide curve*

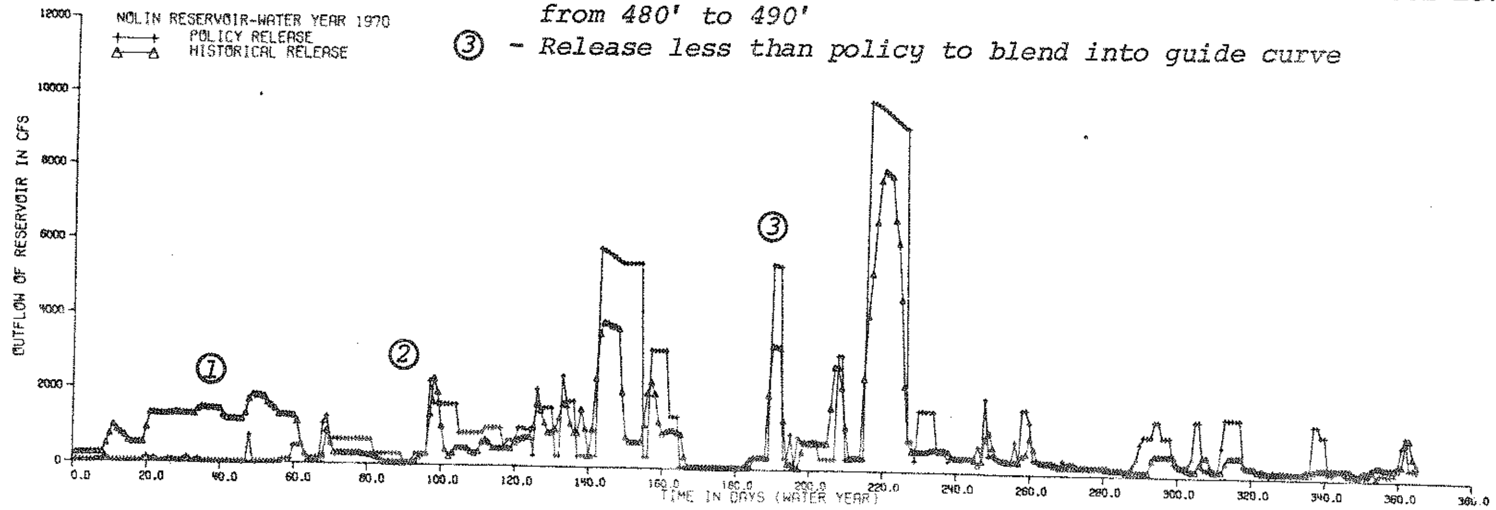


FIGURE VI-8-B - *COMPARISON OF HISTORICAL RESERVOIR RELEASE OBTAINED FROM THE GAGING STATION NEAR DAM WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR NOLIN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR*

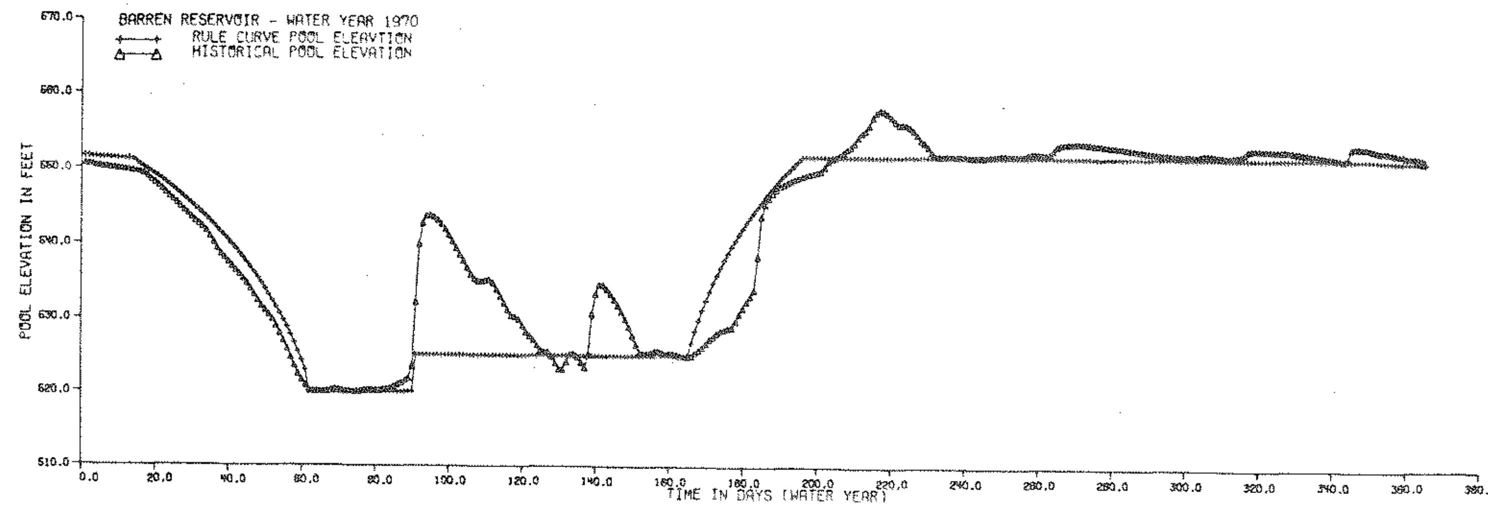


FIGURE VI-9-A – *COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR BARREN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR*

① - *Policy release is much higher than shown to deplete storage in summer pool*

② - *Storage accumulated in Jan. was depleted as rapidly as feasible to lower pool to elev. 519 for state construction work. Due to continued heavy inflow work was rescheduled.*

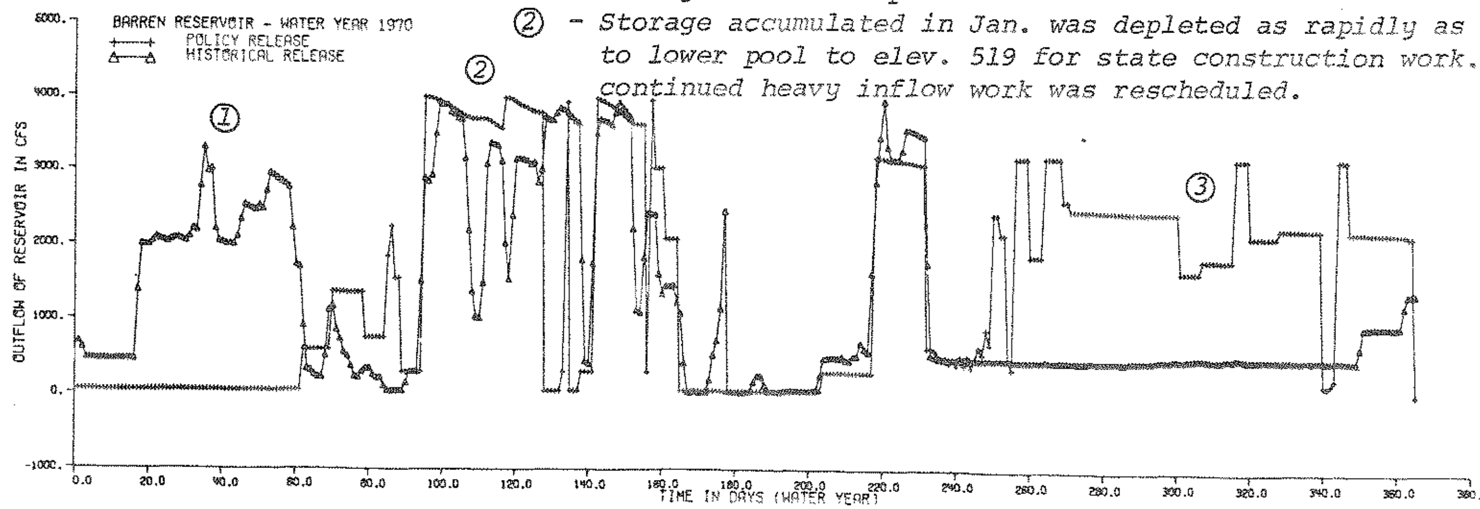


FIGURE VI-9-B – *COMPARISON OF HISTORICAL RESERVOIR RELEASE OBTAINED FROM THE GAGING STATION NEAR DAM WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR BARREN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR*

③ - *Release was less than policy to provide a smooth gradual return to pool. This also avoids rapid variation in downstream flows.*

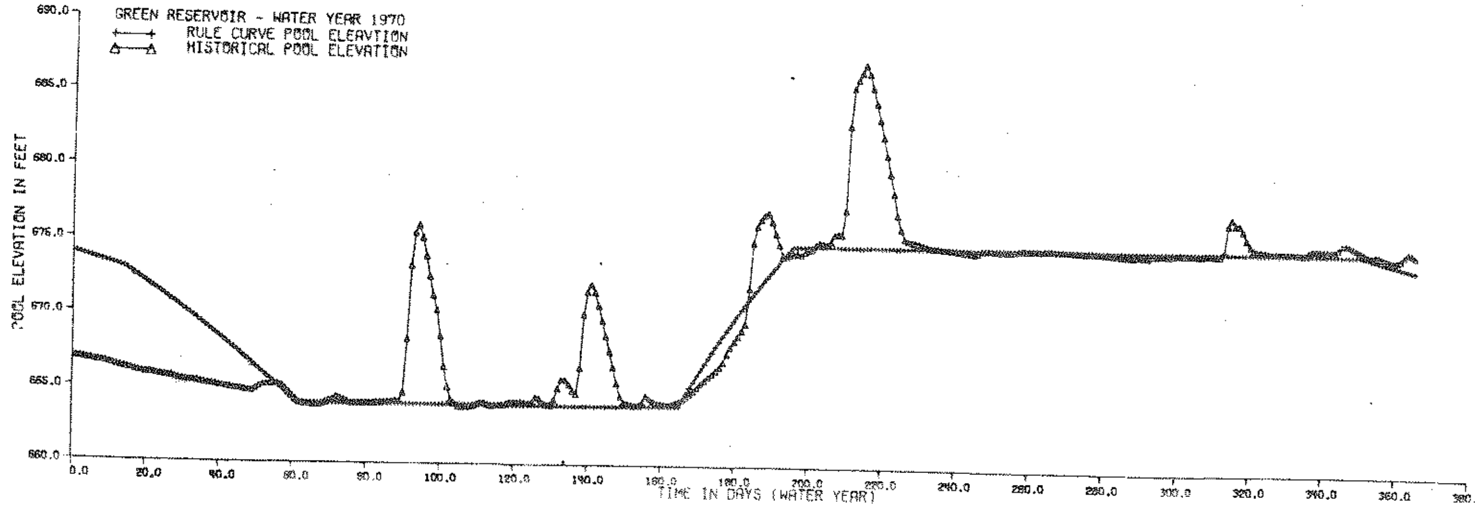


FIGURE VI-10-A - *COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR GREEN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR*

① - *Increased outflow to inspect flooded area @ 8,000 cfs in Greensburg area*

② - *Storage discharged as rapidly as practical to avoid killing trees, for recreation and to regain flood storage capability*

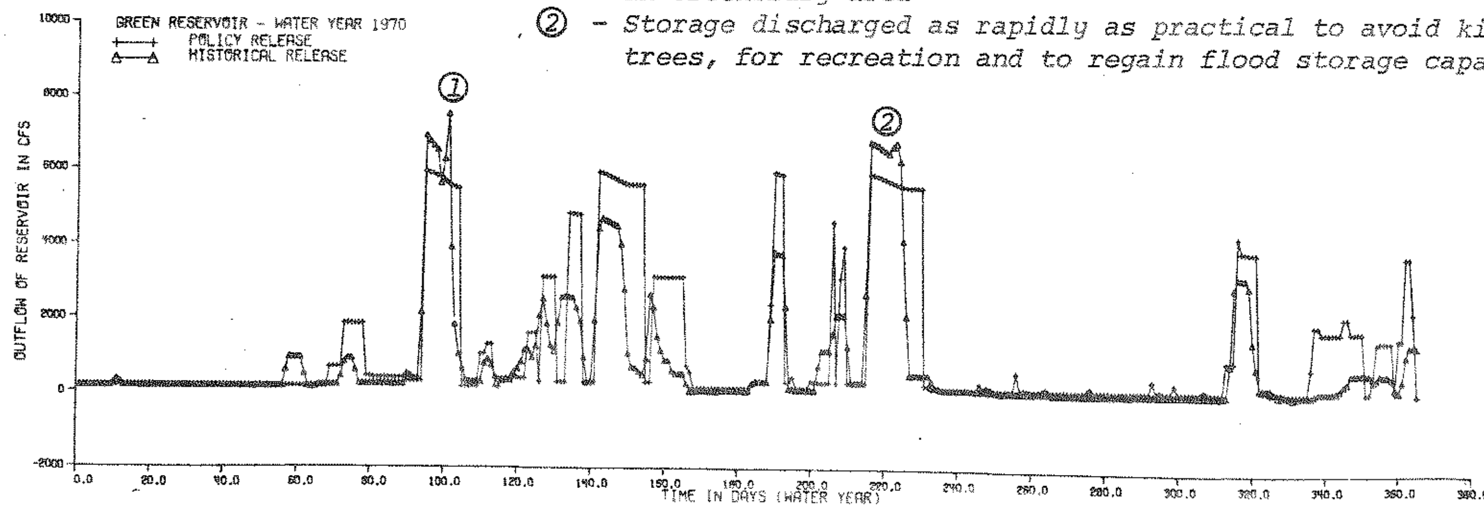


FIGURE VI-10-B - *COMPARISON OF HISTORICAL RESERVOIR RELEASE OBTAINED FROM THE GAGING STATION NEAR DAM WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR GREEN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR*

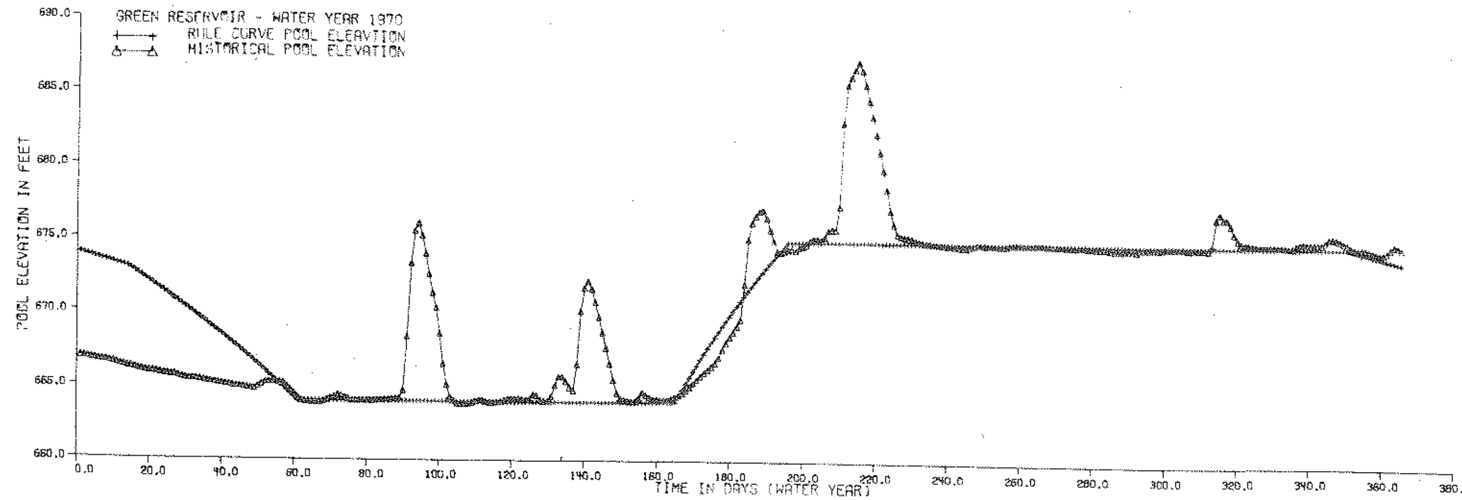


FIGURE VI-10-A - COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR GREEN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR

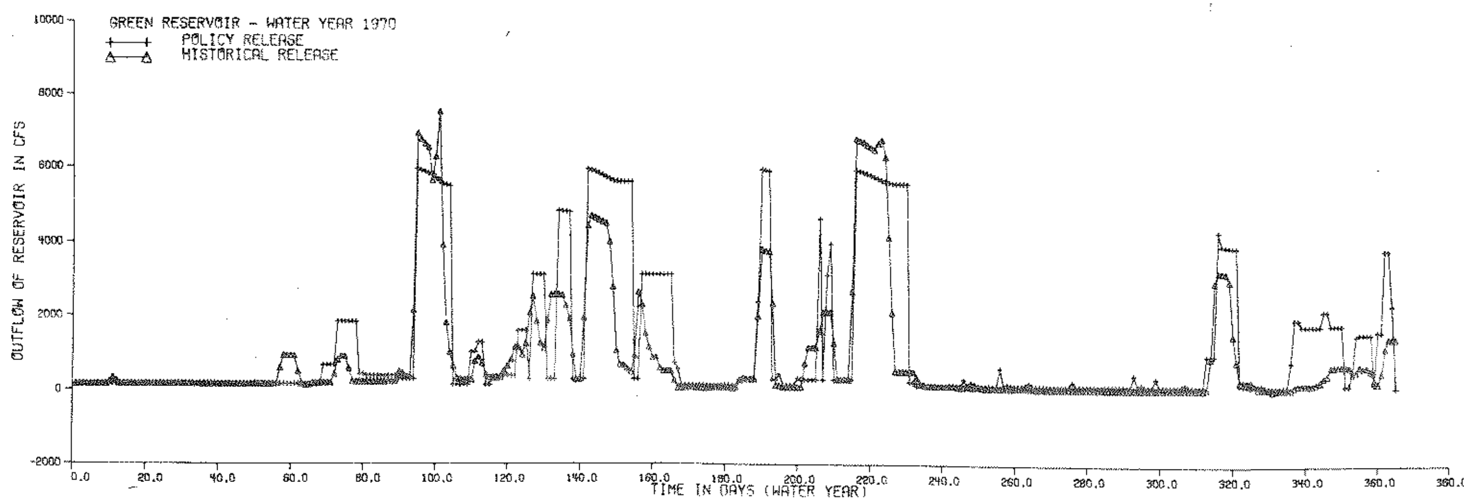


FIGURE VI-10-B - COMPARISON OF HISTORICAL RESERVOIR RELEASE OBTAINED FROM THE GAGING STATION NEAR DAM WITH RELEASE SERIES GENERATED BY THE OPERATING POLICY ALGORITHM FOR GREEN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR

2. *NATURE OF PROGRAM OUTPUT*

The operating policy algorithm yields day t release decisions, Q_t, that (see Fig. VI-11) belong to class A reservoir regulation decisions characterized by:

(a) the use of systems state information for day $t=t_0$ only (except for a refinement for the Evansville and Calhoun stages to be discussed later),

(b) is not influenced by anticipated or probable decision on day $t+\tau$, $\tau = 1, 2, 3, \ldots$ and so on.

In reality, release decisions are made such that (informal) attention is given to precipitation and river stage forecasts throughout the system. The Figure VI-11 clarifies that release decisions projected for say a 5-day period are based on projected data having a steadily decreasing information content (class B). The figure also clarifies (class C) that each day's regulation decision would be an update and that this updating involves an updating of the forecast information.

The Figure VI-12 when taken together with Figure VI-11, clarifies that release decisions constitute only parts of a system's input. In addition to the controllable $\overline{Q}_t$, one has uncontrollable $\overline{X}_{t+\tau|t}$ inputs (side inflow and tributary inflows). Clearly the $\overline{Y}_{t+\tau|t}$, i.e. the result of release decisions may be increasingly uncertain for larger τ whenever the uncontrolled input dominates possible reservoir release decisions.

Finally it is noted that during times of flood, the time step of interest decreases. This may, in effect, increase T_r (measured in time steps).

The Figures VI-11, 12 are intended to point to the complexity of optimal regulation, particularly if one is to pursue optimality of release decisions.

It should be noted that the constructed operating policy algorithm mostly outputs policy release decisions (Q_{tk} (k = reservoir index) on a day by day basis without involving forecasted input or forecasted systems state data (see class A Figure VI-11). Therefore, when deviations between policy and historical releases (shown in the Figures VI-2 thru 10) occur for days on end one should not associate this with a cumulative discrepancy, but merely as a systematic discrepancy that persists.

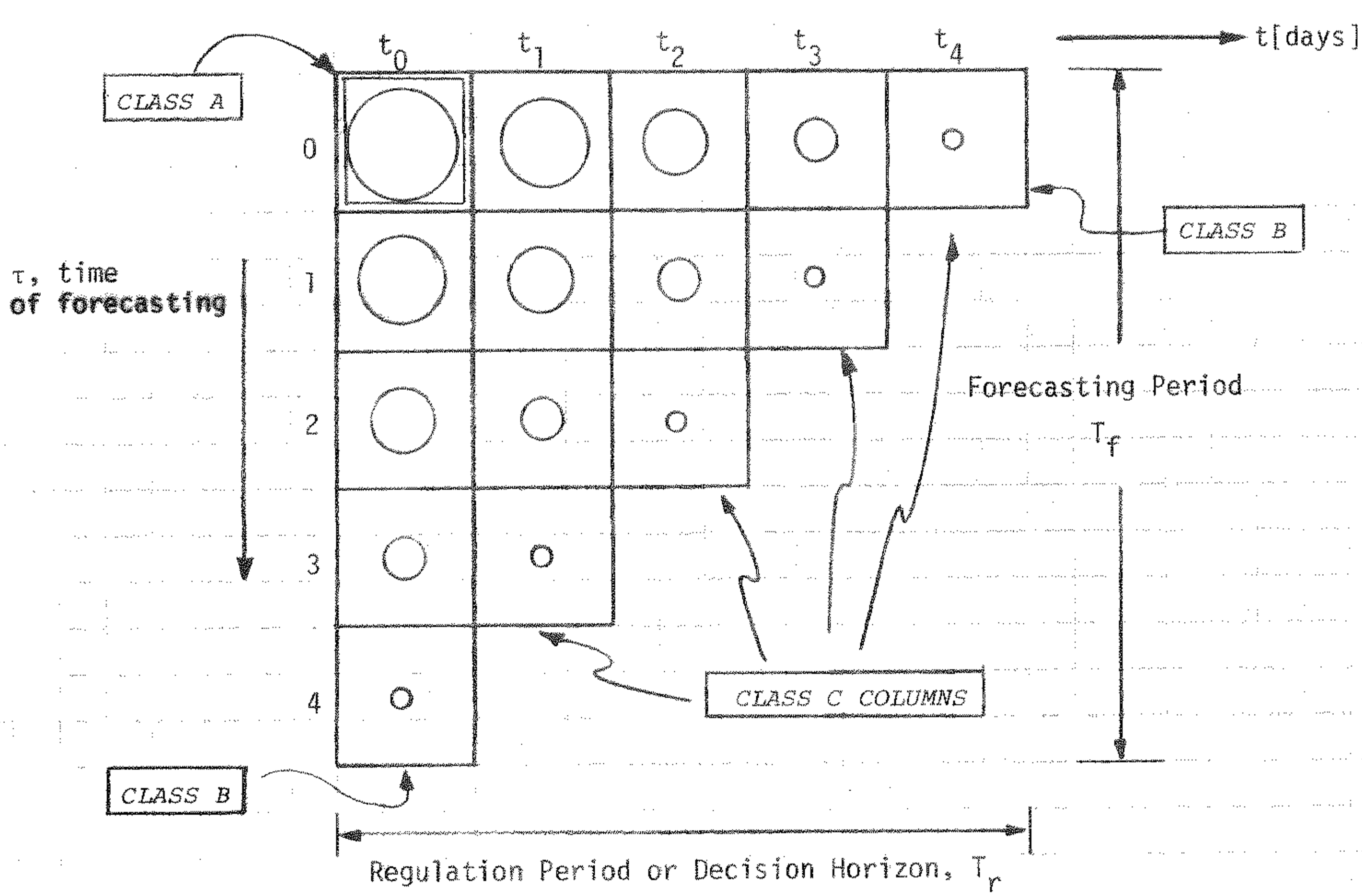


FIGURE VI-11 - RESERVOIR REGULATION DYNAMICS. THE OPERATING POLICY ALGORITHM REPORTED HEREIN REPRESENT A CLASS A INFORMATION DECISION. THIS IS A DECISION BASED ON THAT SAME DAY'S SYSTEMS INPUT AND STATE INFORMATION WHOSE RELIABILITY IS PORTRAYED BY THE CIRCLE SIZE IN CLASS A.

THE GENERAL PROBLEM OF USING FUTURE, I.E. FORECASTED SYSTEMS INPUT AND STATE INFORMATION REQUIRES: (A) BUILDING A GRB SIMULATION MODEL; (B) SEQUENTIAL USE OF THE OPA REPORTED HEREIN. WHILE ON DAY t_o AN "INFORMATION CLASS B" DECISION IS MADE, ON DAY $t_o + \tau$ ONLY A CLASS C DECISION IS POSSIBLE, I.E. A DECISION UTILIZING $4-\tau$ FORECASTED DATA SETS OF STEADILY DECLINING INFORMATION RELIABILITY AS PORTRAYED BY CIRCLE SIZES.

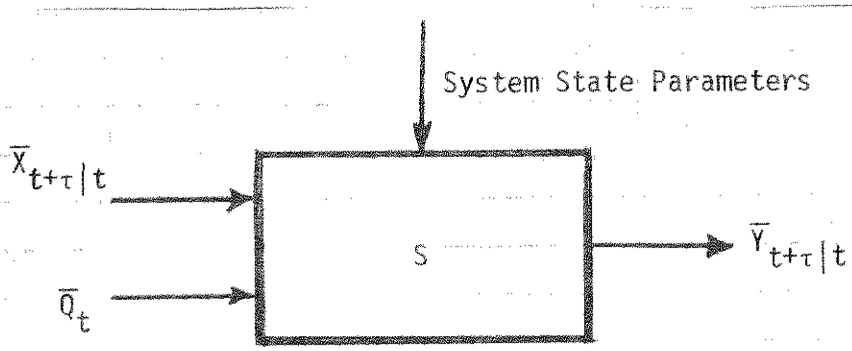


FIGURE VI-12 - THE EFFECTIVENESS OF RESERVOIR RELEASE DECISIONS, $\overline{Q}_t$, IN A SYSTEM (SUCH AS THE GRB SYSTEM) DEPENDS ON THE RELATIVE PERIOD MAGNITUDES OF $X_{t+\tau|t}$ (= UNCONTROLLABLE INPUTS) AND $\overline{Q}_t$.

3. *SUMMARY OF POLICY RELEASE ATTRIBUTES*

A quantitative study of the GRB reservoir systems operation necessarily requires the use of a simulation model. However, the inherent difficulty of simulation of partially controlled systems with random inputs is the volume of the output. The approach taken in output analysis of this study has been to distribute release decisions over a group of mutually exclusive release decision classes. In addition the release decisions are disaggregated with respect to time. In this fashion, one may obtain some kind of statistical analysis of operating policy releases according to two attributes, namely release classes and time period of water years.

The Figure VI-13 shows one such output data analysis. Operating policy releases have been divided over twelve release classes and four periods of the water year. The release classes 1 to 12 have been correlated as much as possible with the classes found in the COE regulation schedules. The lack of a one-to-one correspondence shows the COE specification to be not fully consistent.

The period of the water year and the twelve operating policy release classes have been specified in Figure VI-14.

Among the conclusions that may be drawn from Figure VI-13, 14 are the following:

(a) During the analysis period, the maximum capacity of outlet works was not used (see class 1). In view of the very large flood storage capacities of the GRB reservoirs (ave. 14"), this is not surprising.

(b) The releases in class 3 and class 8 are hardly effective because the storage in the "allowance for deviation" zone is so large.

(c) The releases in class 6 and 12 show relatively small downstream channel capacities for Rough and Barren River Reservoirs and a large downstream channel capacity for Green and Nolin River Reservoirs. Interested parties along Rough and Barren Rivers may be vocal; they may not be vocal or absent along the Nolin and Green Rivers.

ACTIVE CONSTRAINTS (SEE FIGURE V-5)		PLAN 1	PLAN 2 (Systems Controls do not constrain)					PLAN 3 (Systems Controls do constrain)					
COE REGULATION SCHEDULES (SEE FIGURE V-4, APPENDIX A*)		E	A or B	B				C			C+D		
RELEASE CLASSES		1	2	3	4	5	6	7	8	9	10	11	12
Reservoir	Period												
Rough River 1965-1971 2556 days	1	0	971	0	42	116	52	40	0	45	2	16	12
	2	0	282	0	8	27	5	0	0	0	0	0	0
	3	0	88	5	35	297	100	6	0	101	6	47	57
	4	0	100	0	0	11	6	42	0	20	2	8	7
Nolin River 1965-1972 2922 days	1	0	970	0	98	244	10	60	0	63	10	21	6
	2	0	318	0	15	35	0	0	0	0	0	0	0
	3	0	138	14	90	290	0	21	0	124	51	120	0
	4	0	118	1	0	1	0	60	0	26	4	14	0
Barren River 1965-1971 2556 days	1	0	771	0	41	305	47	80	0	43	0	6	3
	2	0	302	0	2	14	4	0	0	0	0	0	0
	3	0	145	0	26	274	28	39	0	96	12	105	17
	4	0	110	0	0	0	0	43	0	26	1	13	3
Green River 1970-1972 1096 days	1	0	342	0	29	105	10	12	0	30	4	17	7
	2	0	116	0	1	20	1	0	0	0	0	0	0
	3	0	84	0	7	43	1	70	0	35	10	57	11
	4	0	45	0	0	0	0	15	0	18	1	3	2

FIGURE VI-13 - SUMMARY OF OPERATING POLICY RELEASE DECISIONS SHOWING NUMBER OF DAYS IN EACH PERIOD OF THE WATER YEAR THAT A POLICY RELEASE FELL INTO THE CLASS THAT ARE SPECIFIED IN FIGURE VI-14

*Note - *Appendix A in the companion report PWRRC Report No. 80.*

PERIOD	1 = Period of Maximum Flood Storage 2 = Period of Spring Filling 3 = Period of Recreation Pool 4 = Period of Fall Drawdown
COLUMN	1 = (Operating Policy) release at maximum capacity of outlet works.
COLUMN	2 = Release Q_{min} if elevation is below rule curve. Otherwise release Q_{min} or Q_{inflow} whichever is greatest. 3 = Release so as to lower elevation to rule curve in one day. 4 = Release to lower elevation at a selected drawdown rate [ft/day]. Various selected rates depending on time of year, etc. are shown in Figure V-5. 5 = Release by keeping gate same as previous day. 6 = Release Q_{max} as constrained by local control stations.
COLUMN	7 = Release Q_{min} if elevation below rule curve; otherwise take Q_{min} or $Q_{inflow} \leq Q_{hold}$, whichever is greatest. 8 = Release to lower elevation to rule curve in one day, but less than Q_{hold}. 9 = Release Q_{hold}. 10 = Release so as to lower elevation at a specified rate (varied) [ft/day]. 11 = Release by keeping gates same as previous day. 12 = Release Q_{max} as constrained by local control stations.

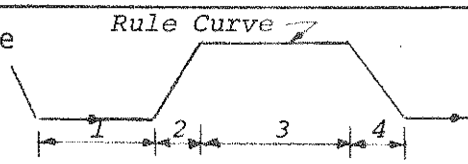


FIGURE VI-14 - SPECIFICATION OF WATER YEAR PERIODS AND OPERATING POLICY RELEASE CLASSES FOR THE TABLE IN FIGURE VI-13.

(d) The releases in class 5 and 11 show that there is an unwritten rule to change gate setting and hence outflow rates as little as possible even during the periods of substantial deviation from the rule curve.

(e) The releases in class 10, 11 and 12 (for which systems controls do constrain so that the reservoir releases should have been Q_{hold}, e.g. 300 cfs) show that the systems constraints were frequently violated.

4. *OTHER SUMMARIES OF OPERATING POLICY RELEASE ATTRIBUTES*

An inspection of the reservoir release data found in Figure VI-2 thru VI-10 makes clear that ordinary time series analysis methods would be inapplicable. The data do result only partially from a natural process. They depend more significantly on human decisions. Inferring these decisions from information such as generated in the Figure VI-2 thru 10, can only be done by referencing the releases to decision determinants. These determinants derive from the simultaneous pursuit of a number of objectives while honoring a large number of constraints which, furthermore, do depend on the time of year. As a consequence, a first approach followed in the analysis of obtained results was to aggregate release decisions into so-called decision and/or constraint classes such as those shown in Figure VI-14. These classes reflect, to a greater or lesser extent, the reservoir regulation objectives. A frequency of occurrence analysis of decisions that associates with the 12 classes and 4 seasons of Figure VI-14 is shown in Figure VI-13.

The resulting distributions represent the most aggregated view of regulation decisions because the decisions falling in various classes are added together for the entire analysis period (up to 7 years).

The Figures VI-13, 14 lead to the 5 conclusions stated in section VI-3. By going to different degrees of disaggregation it is likely that a fair number of additional inferences may be postulated. These different degrees of disaggregation can be accomplished for the historic releases, the stages at all local and systems controls, the historic releases, the stages at all local and systems controls, the precipitation data, etc. They have all been stored on tapes together with the simulated operating policy releases. Thus the data is ready for further analysis. At this moment, however, time and funding are lacking to pursue further work. We can only state which analysis approaches are likely to be fruitful and be alert to future opportunities to implement them.

A first approach would be to use the table of Figure VI-13 on a water year by water year basis. This, in effect will give a seasonal time step length (see top of Figure VI-14). This disaggregation would bring out dependencies on seasonal variation between the years (requiring for a given reservoir a comparison among tables). Furthermore, the time period may be small enough to observe (comparison of entries in given columns of any one table) possible correlations in release decision classes between the four GRB reservoirs (systems operation).

A second approach would be to increase the number of release decision attributes from the two attributes of Figure VI-13 (namely, seasons, or rather periods of the year, and release classes). One could display for these some attributes the total precipitation generating another table with the 4[reservoir] x 4[periods] x 12[release classes] = 192[precipitation magnitudes]. One could then correlate this table of magnitude with the table of release occurrences in Figure VI-13.

A third approach would be to expand further the number of release classes specified by the Figure VI-13, 14. The twelve classes specified in Figure VI-14 associate with fixed constraints on the stages at control stations and the pool elevations in reservoirs. One could add to these fixed constraints other constraints that do depend on the <u>rates of change</u> in stages at systems controls and in reservoir pool elevations or even "elevation zones."

5. *EVENT ANALYSIS*

Additional analysis of the generated deviation series (representing the differences between historical and simulated reservoir releases) requires a further reduction of the analysis time periods, which so far was taken to be the regulation "season" (periods 1, 2, 3, 4 in Figure VI-13, 14). A possible aggregation falling between the above single period and the single day (which is the time step for data series itself), the "event." Deviations and attributes can be aggregated by say flood events, no flood conditions, local floods, basin wide floods, etc.

The event dates would have to be selected by inspection of the generated graphical output such as those in Figures VI-2 and VI-3. A distinction has to be made between single reservoir events, basin-wide events, and events that also cover adjacent basins. The term "event" would cover not only events but also exogeneously induced similarity in reservoir regulations among adjacent river basins, etc.

A sample of such event analysis is given in Figure VI-15 and VI-16. The comments in Figure VI-16 were speculative and based on limited information, i.e. without recourse to further information and the insight that could be provided by Corps of Engineers staff. That information can only be obtained adequately by interviews.

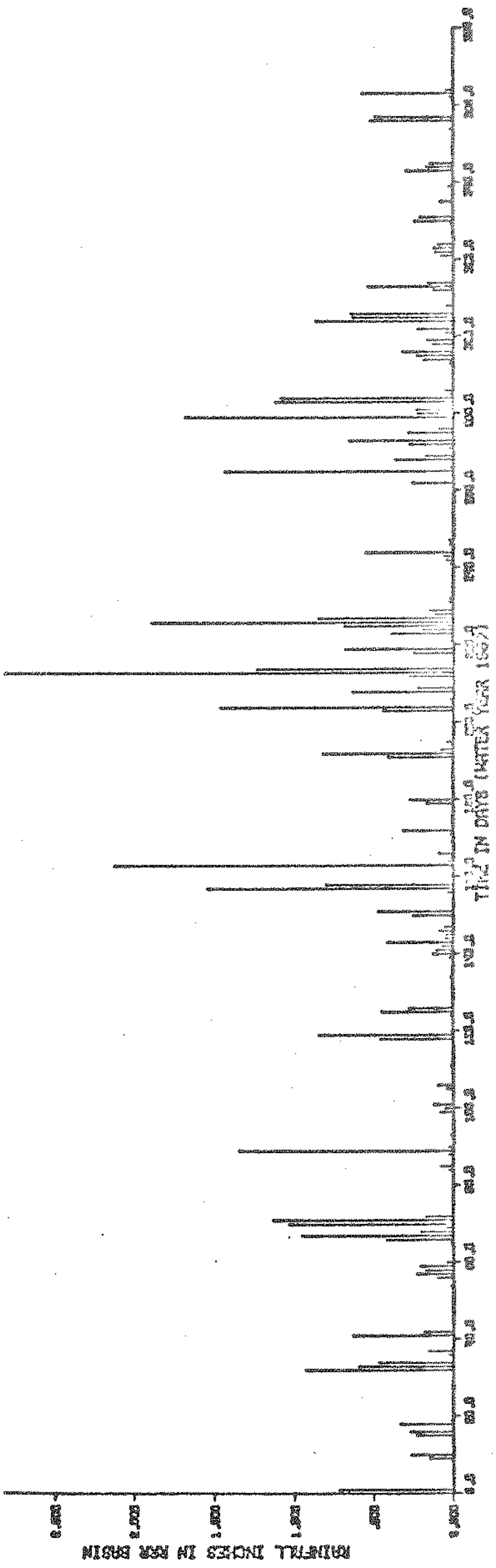


FIGURE VI-15-A - AVERAGE DAILY RAINFALL OVER THE ROUGH RIVER RESERVOIR WATERSHED FOR W.Y. 1967.

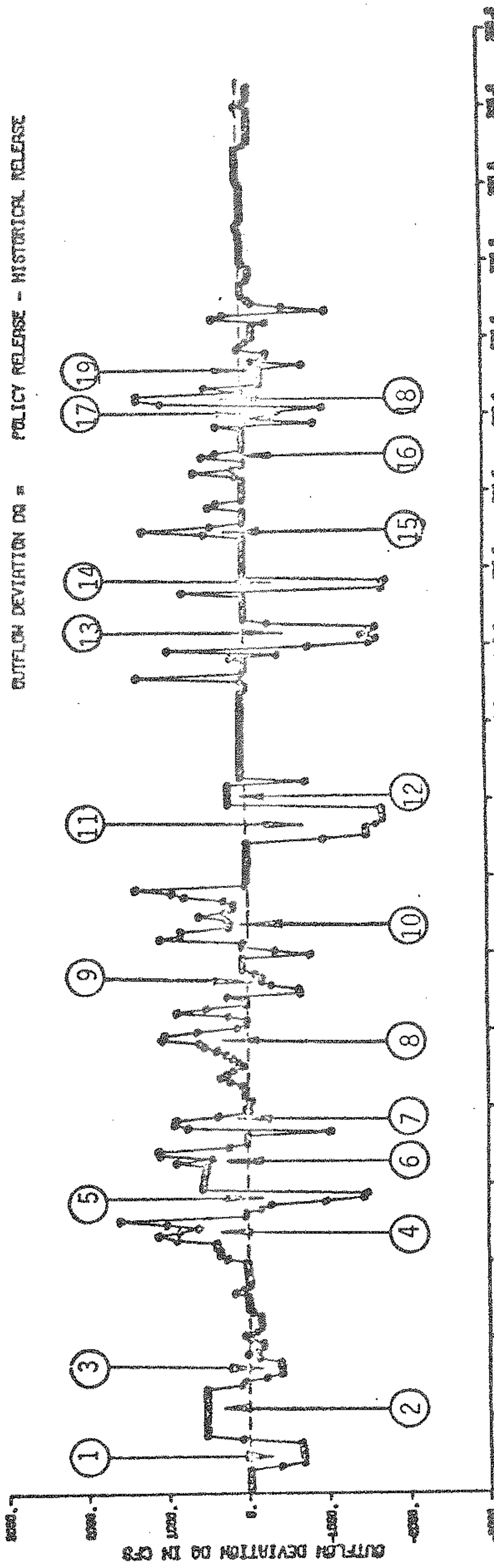


FIGURE VI-15-B - OUTFLOW DEVIATION SERIES FOR W.Y. 1967. THIS SERIES REPRESENTS THE DAILY RELEASES SIMULATED ACCORDING TO THE STATED COE OPERATING POLICY LESS THE ACTUAL OR HISTORIC RELEASES THAT WERE MADE

SYMBOL IN FIGURE 4	PERIOD OF RELEASE DEVIATION	FLOOD RESERVATION USED	POOL ED. ABOVE RULE CURVE	HISTORIC RELEASE LESS SIMULATED POLICY RELEASE		COMMENTS
[-]	[wy - day]	[%]	[ft]	[cfs]	[%]	
1	2	3	4	5	6	
# 4	61-71	0	2	-900	-90	Cannot identify reason for releasing too little.
# 5	74-78	5	11	+1350	1350	The Evansville constraint, prescribing Qp = 100 cfs, was ignored; an 11 ft. deviation of winter pool was apparent reason.
# 6	79-90	2.5	5	-500	-26	Release rate on day 76 was simply continued even though the Evansville control fell below 46 ft.
# 7	95-98	0	0.3	-900	-90	No reason for the low releases is apparent.
# 8	111-121	0	0.2	-1000	-100	No apparent reason for not releasing at policy rates.
# 9	130-135	0	-0.35	300	600	No apparent reason for release.
#10	144-157	0	0.7	-300	-23	No apparent reason for release.
#11	170-178	25	15	+1600	1600	The Evansville constraint which prescribed Qp = 100 was ignored, probably because of pool being 15 ft too high.
#12	179-184	5	3	-200	-10	Small deviation because valve opening was kept at setting on day 175.
#13	185-211	-6	-4	-50	-50	Low flow constraint QP $\geq$ 100 [cfs] was violated in order to fill up pool for recreation season.
#14	220-227	12.5	11.5	1500	1500	The Evansville constraint prescribing Qp = 100 cfs was ignored, probably because pool was 11.5 ft above rule curve
#15	235-237	40	18.0	1700	1700	The Evansville constraint Qp = 100 cfs was ignored to start bringing pool down from +18 ft.
#16	249-251	25	13.0	-1200	-70	Reasons for short decreases in outflow are not apparent.
#17	269-270	8	4.5	-500	-30	Reason for short decrease in outflow is not apparent.
#18	278-282	1	0.8	500	50	No apparent reason for deviation.
#19	283-285	4	2.5	-1300	-93	No apparent reason for deviation.
#20	288-296	1	0.7	250	18	Relatively minor deviation.

Note: *Column #3 - the reference is the available flood control storage on day t as this may be obtained from the rule curve*
Column #6 - the reference is the simulated policy release

FIGURE VI-16 - PRELIMINARY ANALYSIS OF HISTORIC RELEASE FROM ROUGH RIVER RESERVOIR, KENTUCKY, LESS THE RELEASES AS PRESCRIBED BY THE STATED RESERVOIR RELEASE POLICY FOR WATER YEAR 1967

6. *ANALYSIS BY INTERVIEW*

During June 23, 1976, a meeting was held between the staff of the Reservoir Regulation Section, Louisville District Office, Corps of Engineers and the Purdue project researchers. The meeting permitted a superior form of event analysis. Not only were comments received from those thoroughly familiar with the GRB system, but also supporting records were at hand. In addition to the Dam Tender Reports (fully used in this study), for example, there were available Daily Reservoir Bulletins showing information for all GRB reservoirs (including pool elevation, discharge, tail water elevation, and stages as well as discharges at all control points and other important gaging stations). Figure VI-17 shows a sample of such a bulletin for November 8, 1970. Furthermore, there were available monthly reports showing daily values of pool elevation, of inflow and of reservoir outflow for each of the four GRB reservoirs. There were available also monthly reports recording the stages at all three systems controls. A sample of the November 1970 Monthly Report for Nolin River Reservoir is shown in Figure VI-18. It may be compared with the plotted outputs from the operating policy algorithm for days 32 to 62 in Figure VI-19.

As a result of the meeting, COE staff provided an event analysis for 1970 and 1971 operating policy outputs. Typical COE staff member comments are shown in the Figures VI-2, 8, 9 and 10 for year 1970 (Rough, Nolin, Barren and Green River Reservoirs). The graphs plus comments in the Figure VI-19 are for the year 1971 and for Nolin River Reservoir. This year contains the period portrayed in Figure VI-18. Each k in the Figures VI-2, 8, 9, 10 and 19 that pertains to an "event period" rather than single day (which is what the operating policy algorithm produces).

CORPS OF ENGINEERS U. S. ARMY LOUISVILLE DISTRICT	DAILY RESERVOIR BULLETIN *Reports Control Symbol ORLED-10*	DATE 8 NOV 70 / DAY SUN

GREEN RIVER BASIN

RES.	TIME OF OBS.	POOL ELEV. (FT.)	T.W. ELEV. (FT.)	DISCHARGE (CFS) T.W.	DISCHARGE (CFS) CONDUIT	GATE OPENINGS 1	2	3	4	5	6	BYPASS OPENINGS * 1	2
GRR	8A	667.31 (-1.55)	603.79		6070	6/10	7/10	6/10				C	C
NRR	7A	503.23 (-.44)	426.79		127[illegible]	5/100	2/10	C				C	C
BRR	7A	543.52 (-.74)	486.44		3780	4/10	5/10	OUT				C	C
RRR	7A	485.21 (-.77)	439.83		1715	2/10	4/10	2/10				C	C

PRECIPITATION - WEATHER - TEMPERATURES

RES.	TIME OF OBSERVATION	AMOUNT SINCE LAST A.M. OBS. (INCHES)	BEGAN DATE	BEGAN HOUR	STORM TOTAL (INCHES)	ENDED DATE	ENDED HOUR	WEATHER	TEMP PAST 24 HR. MAX.	TEMP PAST 24 HR. MIN.	% F.C. STORAGE UTILIZED
GRR	8A	0						CLR	69	33	
NRR	7A	0						FOG	68	33	
BRR	7A	0						PC	70	36	
RRR	7A	0						CLR	66	33	

RIVER STATIONS

STATION	TIME	STAGE	DISCH.
GREENSBURG	8A	12.65	5755
GRESHAM		5.38	236
MUNFORDVILLE	7A	12.30	6775
BROWNSVILLE	OBS 7A	12.67 12.67	8530
ALVATON	7A	4.51	159
BOWLING GREEN	7A	11.43	9201
LOCK 4 UG 3.09 LG 17.5			
ABERDEEN			
FALLS OF ROUGH	7A	12.04	1625
DUNDEE (RADIO)	7A	13.31	1776
DUNDEE (OBS.)			
HORSE BRANCH	7A	2.10	6
GLEN DEAN	7A	4.00	0

	AFTERNOON POOL READINGS TIME	ELEVATION	* PRESENT MULTI-LEVEL OPENINGS UPPER	MIDDLE	LOWER	NUMBER
GRR	4P	668.28	—	—	—	1&1
NRR		503.50	C	C	C	—
BRR		544.03	C	C	C	—
RRR		485.70	—	—	—	—

OUTLET OPERATIONS

	PREVIOUS 24-HOUR PERIOD TIME	TOTAL GATES	TOTAL BYPASS	ANTICIPATED WITHIN NEXT 24 HOURS TIME	TOTAL GATES	TOTAL BYPASS	DISCHARGE
GRR	NC			NC			
NRR	NC			NC			
BRR	NC			NC			
RRR	NC			NC			

REMARKS TW TEMP GRR 15.5 AT 230P
NRR 15 AT 2PM
BRR 16 AT 2P
RRR 15.5 AT 2P

ORL Form 194 12 Jul 61 REVISED MAR 69 *Precipitation data on back of sheet* Engineering

FIGURE VI-17 - A SAMPLE OF DAILY RESERVOIR BULLETIN OF THE GRB SYSTEM FOR NOVEMBER 8, 1970

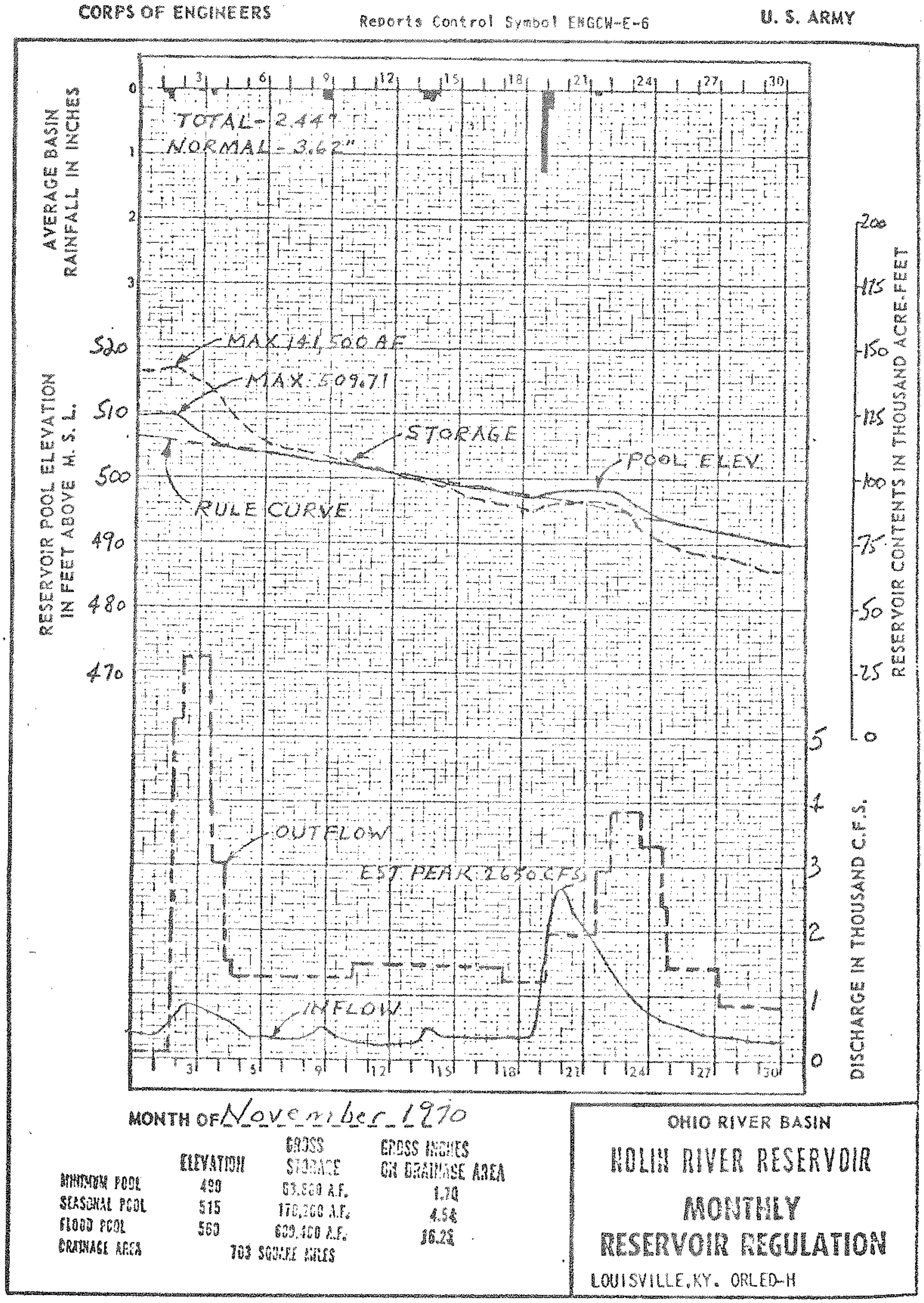


FIGURE VI-18 - A SAMPLE OF MONTHLY REPORT FOR THE REGULATION OF NOLIN RIVER RESERVOIR DURING NOVEMBER 1970

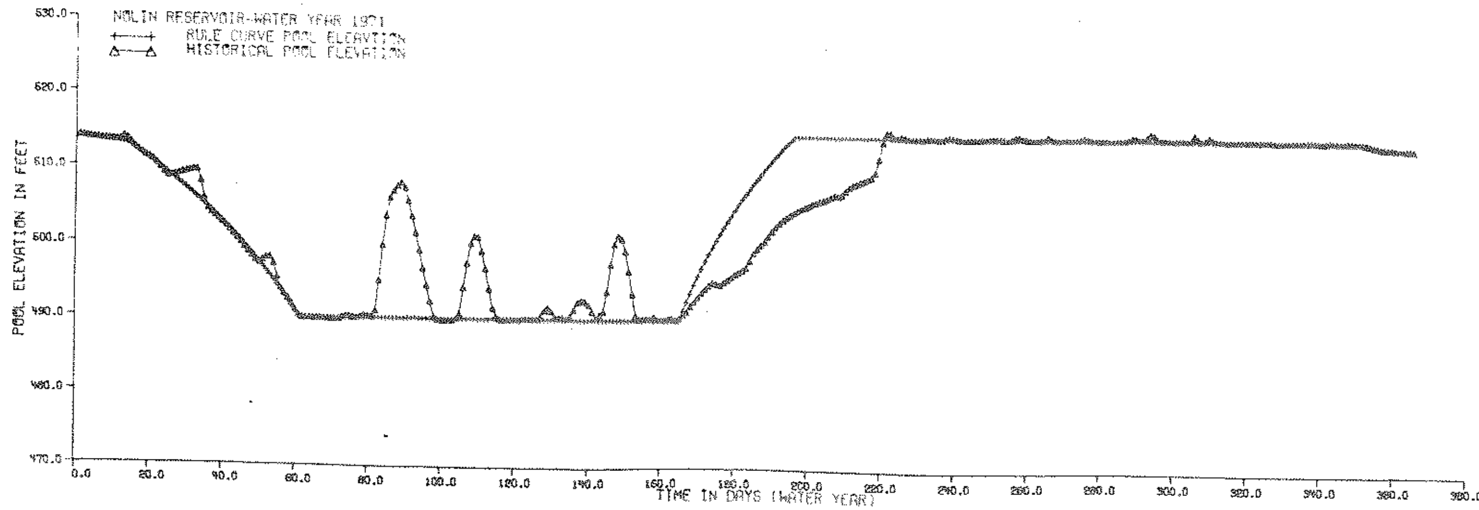


FIGURE VI-19-A - COMPARISON OF RULE CURVE AND HISTORIC POOL ELEVATIONS FOR NOLIN RIVER RESERVOIR, KY, FOR THE 1970 WATER YEAR

① - *Special regulation to facilitate construction work on Dam #1 Green River*

② - *Gates 1 & 3 fully opened to observe outlet conditions*

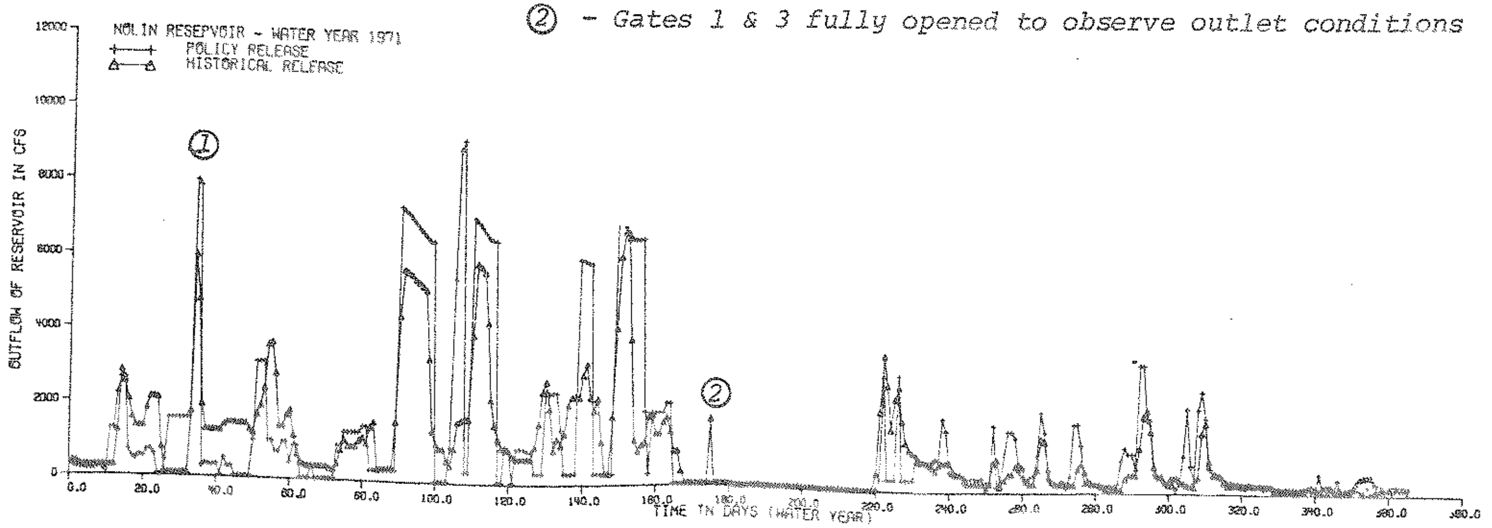


FIGURE VI-19-B - COMPARISON OF HISTORICAL RESERVOIR RELEASE OBTAINED FROM THE GAGING STATION NEAR DAM WITH RELEASE SERIES GENERATED BY OPERATING POLICY ALGORITHM FOR NOLIN RIVER RESERVOIR, KY, FOR THE 1971 WATER YEAR

VII. OPERATING POLICY ADAPTATIONS

1. *GENERAL DEFINITION*

The original intent of the research reported herein was first of all to investigate and report operating policy adaptations for one or several reservoir systems and secondly to identify their causes. Operating policy adaptations may be regarded as modifications of the strategy for pursuing the objectives formulated for the water resource systems. This strategy was called the "long-run" operating policy. It is most clearly embodied in the rule curve. Actually the major effort has gone into researching the tactics used to implement the strategy. These tactics are the "short-run" components of the reservoir systems regulation. Their study has involved constructing an operating policy algorithm. This algorithm and its results have been discussed extensively in this report and its companion publication, PWRRC #80.

In this chapter the long-run policy changes or operating policy adaptations will be reported. All adaptations reported in Sections VII-3, 4, and 5 have been gleaned from the supplement of the GRB Master Manual and from the regulation schedules information sent by the Cincinnati Division Office and the Louisville District Office over a period of years.

2. *SPECIFIC DEFINITION*

The reference for defining operating policy adaptations consists of regulation schedules as designed during the reservoir design periods. It is inevitable that those initial regulation plans are modified. Actual operating experiences, addition of reservoirs to a system, and other adaptations due to changing social and economic conditions lead to such changes.

Typical adaptations may be classified as follows:

(a) changes in the rule curves. This may cover changes in pool elevation for the flood season, changes in recreation pool, change in the length of the recreation season, changes in filling these reservoirs and changes in the reservoir drawdown.

(b) changes in maximum allowable release Q_{max}. This mostly associated with the channel capacity. In turn, these restrictions may have a physical basis (channel aggradation, channel constriction by vegetation) or may result from pressure by downstream interests.

(c) changes in control station configuration. This may or may not associate with point (b) conditions.

(d) changes in the minimum release flow, Q_{min}. This may result from water quality demands.

3. *ADAPTATIONS EFFECTED PRIOR 1966*

(a) Change in Q_{max} for Barren River Reservoir from Q_{max} = 8000 cfs to Q_{max} = 6000 cfs during the winter season and 4000 cfs during the crop season. The change followed complaints by downstream interests.

(b) Rule curve changes for all reservoirs such that filling commences on April 1 as fast as possible.

(c) Rule curves changes for all reservoirs such that drawdown commences on August 1 with a completion target date of November 30.

4. *ADAPTATIONS EFFECTED IN 1966*

(a) Changes in rule curves for all reservoirs to advance the start of the filling rate from April 1 to March 15.

(b) Rule curve changes for all reservoirs to delay drawdown from August 1 to September 15 (starting date).

(c) Changes in rule curves prescribing the low drawdown rate from September 15 to October 15 and a high drawdown rate from October 15 to November 30. The adaptations (a), (b), and (c) were effected as a result of numerous requests from state, county, muncipal and other interests to extend the seasonal pool for recreational activities. Visitation and facilities use associated with the reservoir projects exceeded expectations.

(d) Increase in low flow (amount could not be ascertained) in the lower Green River at the TVA Paradise Steam Generating Plant.

(e) Changes in the Q_{max}-tables associated with decreasing downstream channel capacities. These changes held for all four reservoirs.

(f) Changes in control stations. A new systems control station, namely Lock 4, was added to the existing Evansville and Lock 2 control stations.

(g) Change in local control station for Rough River Reservoir. The Dundee station was replaced by the stations at Glen Dean and Horse Branch.

5. *ADAPTATIONS EFFECTED IN 1970*

(a) Changes in rule curves. The minimum pools were raised at all reservoirs except for Green River Reservoir. This may be due to new insight in the hydrology of the region, or to recreational visitation during the winter, or to locally heavily sediment deposit in the reservoir, or to a combination of these.

(b) Change in Q_{max} tables. The second decrease in maximum allowable release flows no doubt associated with downstream channel capacity decreases.

(c) A numerical statement of these and other adaptations have been collected in Table VII-1. It is noticed that although these adaptations became officially effective on January 1, 1970, some were practiced earlier. For example, adaptation 5 in Table VII-1 seems to have been practiced since 1965. This may be inferred from the historic release data Q_{ht}.

DESCRIPTION OF CHANGE	ROUGH RIVER RESERVOIR	NOLIN RIVER RESERVOIR	BARREN RIVER RESERVOIR	GREEN RIVER RESERVOIR
1 Minimum pool elevation (ft. msl.)	465 to 470	480 to 490	520 to 525	--
2 Average Filling rate during March 15 to April 13 (cfs)	1680 to 1520	2200 to 1780	3530 to 3200	--
3 Average depletion rate furing Sept. 15 - Oct. 14	160 to 150	215 to 180	340 to 320	--
4 Average depletion rate during Oct. 15 - Nov. 30	985 to 870	1290 to 1020	2070 to 1840	--
4 Maximum	3000 to 2000	--	6000 to 4000 (Dec - Mar) 4000 to 3200 (Apr - Nov)	8000 to 6000

FIGURE VII-1 - CHANGES OF OPERATING POLICIES FOR FOUR RESERVOIRS IN GRB SYSTEM (Effective January 1970)

6. *FURTHER DISCUSSION*

It does not appear that dossiers exist that are kept up-to-date and which detail the changes in long-run reservoir operating policies. The contribution to, detraction from,or addition of existing or new reservoir management objectives does appear to be handled in an incidental manner. The physical studies or the various factors that underly each long-run adaptation would, strictly speaking, need to be complemented by evaluation studies of a type normally undertaken in a Planning Division rather than the Engineering Division. At the same time, such studies could hardly be made without the aid of a certain type of simulation model. The type of simulation model suitable for that purpose would have to concentrate on regulation and would have to sufficiently resemble the current regulation procedures. The study reported herein is of that type. Since it requires completion by adding a better handling of forecasted events, we conclude that operating policy adaptations were probably made without the availability of integrated engineering-planning-economic evaluation studies.

If so, a search of files at the Board of Rivers and Harbors to abstract operating policy adaptations cannot be expected to yield quantitative trade-off data in a manner originally visualized.

This does not mean that a search of those files would not be a valuable project. It does mean, however, that in order to really assess the impact on various objectives of proposed and made operating policy adaptations, simulation models are likely to be needed. The file search and model development should be carried on in an integrated manner if not simultaneously.

The possible benefits of such models are as follows:

(a) they can assist in improving short-run operations, i.e. the methods and outcomes of day-to-day regulation,

(b) they can be used to generate the physical consequences of contemplated long-run adaptations,

(c) they constitute the natural link between engineering, planning, and project evaluation work,

(d) they facilitate making explicit the multi-objective trade-offs which reservoir regulation does now establish implicitly.

VIII. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. *SUMMARY*

The study reported herein is an analysis of the historical day to day regulation (operation) of an actual surface water reservoir system, namely the four reservoirs in the Green River Basin, KY. This system is regulated (operated) by the Corps of Engineers, via the Louisville District's Reservoir Regulation Branch. The analysis was made to ascertain:

(a) changes in long-run as well as short-run regulation schedules and regulation practices, herein called "operating policy adaptations," which have been made to adapt to changes in social objectives such as recreation and environmental quality,

(b) adaptations due to changes in physical systems features, such as decreases in downstream channel capacity, the addition of reservoirs to the system, new river regulation works, etc.,

(c) adaptations due to increases in data, growth in data handling capability, and innovations in analysis, particularly in the areas of systems analysis procedures, modeling methods, computer facilities and plotting machines.

At the same time it was hoped that the study could provide systems analysists anywhere with increased insight into real-life constaints, real trade-offs, institutional adaptations and a notion as to how much of a policy space exists in actual systems operations. Its absence would mean that systems analysis methodology can not be applied before some established rules are displaced. That would in itself be ample justification for a detailed empirical study of what is actually being done in reservoir operation.

The principal tool used in this study was a simulation model of the daily reservoir regulation practices. The result, called "operating policy algorithm," was used to generate continuous series of so-called "policy releases, Q_t." The deviations between the policy releases and the historical reservoir releases, $Q_{h,t}$, were analyzed with a three-fold purpose, namely,

(a) to improve and refine the operating policy algorithm,
(b) to define the extent and effect of remaining incidental factors,
(c) to ascertain long-run changes or long-run adaptations in these operating policies of any or all of the Green River Basin reservoirs.

Typical of the work reported herein is the use of "Dam Tender Reports." These daily data sheets for each of the GRB reservoirs permitted abstracting:

(a) historic reservoir release series, $Q_{h,t}$,
(b) historic pool elevation, $Z_{h,t}$,
(c) historic reservoir inflow series $Q_{in,t}$.

The definition of the $Q_{in,t}$ series required the construction of reservoir inflow models. In turn these models required other data series such as precipitation and evaporation during the periods of the reservoirs' existence. The construction and implementation of the operating policy algorithm required yet additional data, namely, the stages, $Z_{c,t}$, at a number of control stations. Because of the up to nine years of records for a large number of stations at which precipitation, temperature, evaporation and/or streamflow data were measured, an efficient data base had to be and was constructed as part of the study.

Special attempts were made to ensure that field-level information was used in the study. Initial contacts were made at the Board of River and Harbors, Washington D.C. and at the COE Institute of Water Resource Research, Alexandria, VA. Earlier contacts with the COE Ohio River Diviison and Louisville District Office were exapnded. Furthermore, the 1969 proceedings of an HEC seminar on "Reservoir System Analysis" were taken as one of the points of departure. Also the well-known HEC simulation programs were scrutinized.

A partial analysis was made of the deviation time series. It involves the association of daily flow deviations, $Q_t - Q_{h,t}$, with constellations or classes of constraints. The analysis is incomplete. It requires further disaggregation of data and further "operating event analysis." The latter must be undertaken together with COE staff. Time and resources on the part of COE may or may not be available.

2. CONCLUSIONS

(a) It has been possible to build an operating policy algorithm that simulated historic reservoir regulation decisions (for a 24-hour time step) for a four-reservoir system (Green River Basin Reservoirs, KY) regulated by the Corps of Engineers.

The simulation algorithm yielded much insight in field-level regulation practices and their adaptations to changes in social objectives, and to increases in knowledge about the system, and to growth in analysis capabilities.

(b) An analysis of deviation series (i.e. the day by day differences between a reservoir's policy release rate, Q_t, and the historic release rate, $Q_{h,t}$) which represents a principal product of this study has only been completed partially. It was done for the highly aggregated release deviation data found in Figure VI-13. Time is lacking to fully extract the wealth of information contained in the release deviation plots of which Figures VI-2 thru VI-10 are samples. This lack of time does include that of COE staff. Without their input , a satisfactory event-by-event analysis of the deviation time series is not feasible.

(c) Insight in (i) real-life constraints, (ii) informal but necessary trade-offs, (iii) institutional factors, and the need for (iv) judgement, and (v) changes in operating time step, was gained. Once these insights are complimented by a fuller analysis of obtained data, the whole should be quite valuable to systems analysts who conduct research on how to improve reservoir operating optimization methods.

(d) The final operating policy algorithm leaves room for improvement. In particular, the regulator's awareness of and reaction to forecasted precipitation and river stage data needs to be incorporated more fully. While it is unlikely that a complete equivalent for experience can be incorporated in a model, much more could be done. This requires however, a more intense cooperative effort between Agency Staff and researchers.

(e) Contact with the Chief of Engineers' and WRI offices at the national level was not particularly effective. Without the cooperation of the District and Divisions Offices, the present study could not have been completed. With initial results in hand a second contact with COE staff at the national level is considered to be useful.

(f) Despite agency cooperation data collection and handling needed as part of the project, was a much underestimated task.

(g) Generalizing from the relative inaccessibility of data (say Dam Tender Reports), and at the same time, the possibility of enhancing their utility (say of Dam Tender Reports) it is tentatively concluded that much more data is routinely collected and subsequently under-utilized.

(h) Definite long-run adaptations of operating policies were in evidence. The major causes are: (i) larger than expected demands from numerous recreation interests; (ii) well-developed communication with downstream interests, both private and institutional.

(i) No evidence was found that formal, multi-objective trade-off analyses were made on which to base long-run adaptation decisions. At the same time, several adaptations seemed forced by physical factors such as channel aggredation, bank coving due to more extended large flow release periods, channel constrictions due to the not-clearing of downstream river channel by severe floods, etc.

(j) Improving Reservoir Operation depends not only on better, more complex operating policy algorithms, but also on having a complete, well-verified simulation model for the entire Green River Basin.

3. *RECOMMENDATIONS*

(a) A wealth of generated reservoir operations data in the form of differences between historic reservoir releases and simulated operating policy releases (so-called deviation series) is available for the Green River Basin Reservoir System. Only an initial analysis has been made of the deviation series data. It is recommended that a fuller analysis be undertaken.

(b) The analysis recommended in (a) should involve "event analyses." The most typical events are particular floods. These operating event analyses must be made by or in conjunction with COE staff.

(c) The operating policy algorithm should be improved further by introducing additional operating heuristics that are developed via interviews with reservoir regulation staffs. In addition, certain inconsistencies and incompletenesses are to be reduced.

(d) In order to advance the art of optimal reservoir systems operation a total GRB systems simulation model needs to be built. The model components should accept forecasted data among their inputs. A schematic for the model is shown in Figure VIII-1.

(e) A total GRB systems simulation model incorporating an "operating policy simulation algorithm" needs to be built also in order to ascertain whether it provides a suitable nucleus for increased computer assisted reservoir operations in the Green River Basin.

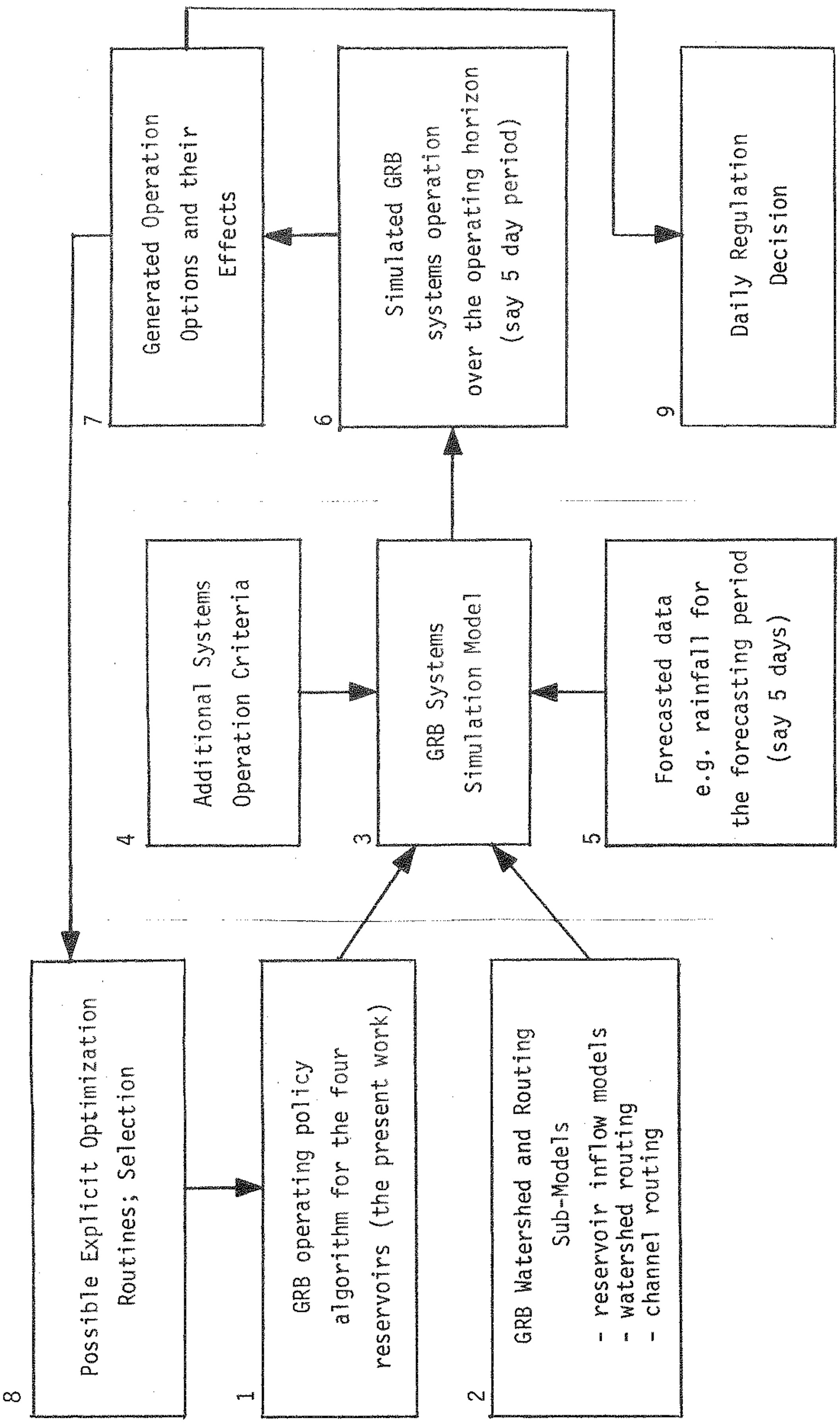


FIGURE VIII-1 - *SKETCH TO ILLUSTRATE STRUCTURE OF RECOMMENDED GRB SYSTEMS SIMULATION MODEL.*

Note: the work reported herein concentrates on Block #1.